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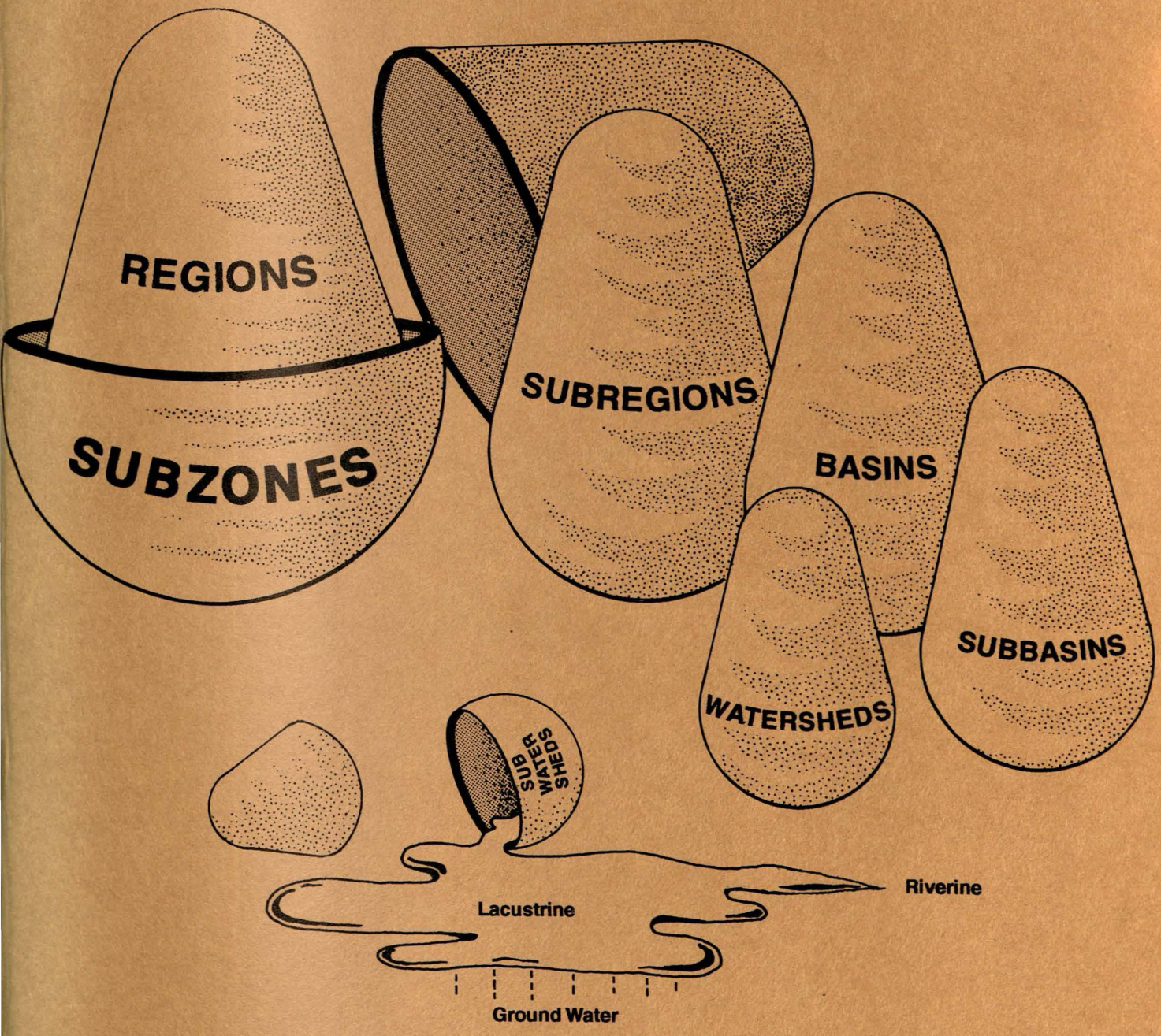
Report **NC-176**

A Hierarchical Framework of Aquatic Ecological Units in North America (Nearctic Zone)

James R. Maxwell, Clayton J. Edwards, Mark E. Jensen, Steven J. Paustian, Harry Parrott, and Donley M. Hill



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INTRODUCTION

Aquatic systems include oceans, estuaries, streams, lakes, wetlands, and ground water. This paper focuses on streams, lakes, ground water, and hydrogeomorphic properties of wetlands. To assess aquatic ecosystems, we must consider the past, current, and likely future states of the physical and biological components of these systems. Having such knowledge requires that aquatic physical and biological patterns at different spatial scales be characterized to meet multilevel planning needs.

To explain changes in aquatic patterns, we must understand the role that biophysical environments such as land and stream types, disturbance events such as floods and fires, and biotic processes such as migration and speciation play in forming the types of patterns observed. These agents of pattern formation (Bourgeron and Jensen 1994) commonly exhibit a high degree of covariance which allows land managers to spatially display such relations through multiscaled biophysical environment (ecological unit) maps (USDA 1993). For example, the climate and physiography of a watershed have been shown to constrain the observed range of aquatic ecological and biotic processes.

Recognizing the importance of these relationships, the ECOMAP work group of the USDA Forest Service directed that a national hierarchical framework for classifying and mapping aquatic ecological units be developed. This framework is linked with terrestrial systems and complements the hierarchy of terrestrial ecological units (USDA 1993). The objectives of this report are to provide:

1. A generic hierarchical framework for characterizing aquatic ecosystems.
2. A description of linkages between terrestrial and aquatic biophysical environment maps.
3. Primary map unit criteria for hierarchical mapping of aquatic systems.
4. Classification criteria to be considered in describing the form, function, and evolution of aquatic systems at various spatial scales.
5. Standardized terminology to be used in the classification, mapping, and inventory of aquatic systems.

The purpose of this report is to provide a framework that ensures consistency in the classifying and mapping of aquatic systems. The goal is to improve ecological analysis of aquatic systems to reflect their varied forms and functions.

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Framework Summary

Ecosystem management requires an understanding of interactions between biotic and abiotic components of ecosystems at multiple spatio-temporal scales (USDA 1993). Three types of map information combine to describe these interactions and to analyze ecosystems: analysis areas, ecological units, and resource status.

Analysis areas define the ecosystems of interest (ecoregions, watersheds, forest stands, etc.) for a given purpose. They may be delineated at various scales to meet multilevel planning and project needs, and commonly include socioeconomic, biological, and physical criteria (USDA 1993). Ecoregion maps (Bailey 1983, Omernik 1987) are an example of coarse-scale ecosystem analysis areas that have proven useful for regional aquatic planning and analysis (Gallant *et al.* 1991).

Descriptions of ecosystem potentials require maps of biophysical environments that are commonly referred to as **ecological units** (USDA 1993). Ecological unit maps delineate physical and biological systems that are relatively stable at a given scale of ecosystem description. They use features that exert primary control on ecosystem processes and patterns in their construction.

Resource status maps describe the existing or historic status of various resource components for environmental analysis (Jensen *et al.* 1991). These maps describe ecosystem components that display high temporal variability for a given scale of mapping and commonly include data collected from traditional vegetation, wildlife, and aquatic surveys.

The components of ecological units (climate, geology, landform) are not changed by management, so ecological unit maps may be used to consistently describe similar biophysical environments for ecosystem assessment (Bailey *et al.* 1994). Ecological units provide a stable template for assessing factors changed by management and for describing the historic or current status of an ecosystem.

Resource status data are combined with ecological unit maps to determine the condition of ecological units. The effects of management are best described by contrasting the current or historic status of an ecological unit with similar, reference ecological units. The natural variability in ecosystem form and function among sites is thus accounted for, so observed differences in resource status may be better correlated to the treatments imposed.

This report presents a hierarchical framework for classifying and mapping aquatic ecological units based on biophysical factors that (1) display low temporal variability at a given map scale, and (2) strongly affect the types of ecosystem patterns and processes that occur in aquatic systems. It expands on the work of Cowardin *et al.* (1992) and addresses the three major aquatic systems that occur widely on National Forest System (NFS) lands: the ***riverine*** system of streams and rivers; the ***lacustrine*** system of lakes and open-water wetlands; and the ***ground-water*** system of aquifers. Hydrogeomorphic criteria are also proposed to refine existing wetlands classifications (Cowardin *et al.* 1992).

Three types of biophysical environments are recognized in this framework: geoclimatic, zoogeographic, and aquatic systems. Each environment is hierarchical and may be used for multiscaled classification and mapping. Ecological unit maps of aquatic ecosystems are constructed by using one or more of these biophysical environment map themes. Aquatic systems (riverine, lacustrine, ground water) are usually shown on separate maps of proper scale. The geoclimatic and zoogeographic settings that such aquatic systems are nested within are displayed on other maps.

Aquatic ecological units are constructed by describing an aquatic system in context of the geoclimatic and zoogeographic settings in which it is most immediately nested. For example, riverine networks may be stratified into valley segment types and differentiated based on their types of landtype association and subwatershed settings (fig. 1).

Geoclimatic Setting

Watersheds and aquatic systems with similar climate and physiography often have similar ecological patterns and processes (Bailey 1983, Hack 1957, Strahler 1957). This geoclimatic setting affects the hydrologic processes (magnitude and frequency of events) that create patterns in aquatic systems. Geoclimatic settings

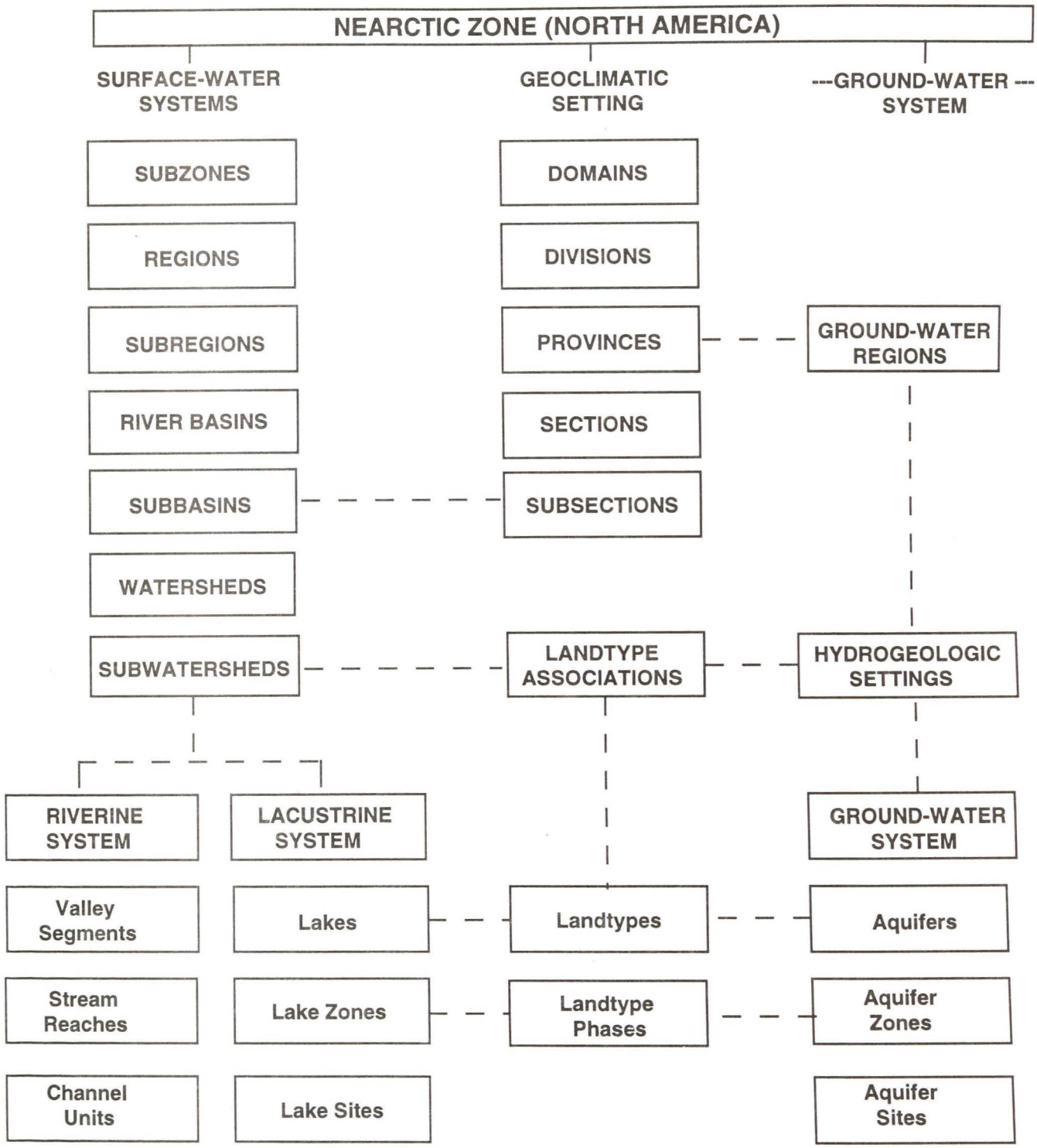


Figure 1.—*General framework of aquatic ecological unit hierarchy. Sizes of units decrease from top to bottom. Larger hydrologic units and ground-water regions are regionalized based on zoogeography and physiography. Smaller aquatic systems are classified based on biophysical criteria and are nested within these overlying settings. Primary functional linkages between aquatic systems and terrestrial (geoclimatic) systems are shown as dashed lines.*

also influence zoogeographic distributions of aquatic biota and govern arrangements of aquatic habitats. Geoclimatic information is used to group watersheds for improved analysis and management. Criteria for classifying and mapping geoclimatic settings are in the national hierarchy of ecological land units (USDA 1993) and should be applied at all levels of the aquatic hierarchy.

Zoogeographic Setting

Hydrologic units contain linked aquatic networks that significantly affect the biotic components of aquatic systems. Hydrologic units have affected speciation because their boundaries have isolated aquatic populations. At the upper levels of the hierarchy, aquatic zoogeography (Poff and Ward 1990) is used to stratify hydrologic units. These units contain groups of aquatic populations that have been isolated by geomorphic and biotic co-evolution to explain historic patterns of native species distributions (Moyle and Cech 1988). At lower hierarchical levels, zoogeographic, geoclimatic, and morphometric information is used to describe watersheds and subwatersheds.

Riverine System

The riverine system consists of stream networks in watersheds. Stream networks are divided into valley segments based on hydrogeomorphic factors. Valley segments are divided into stream reaches based on geomorphic and other factors. Stream reaches are divided into channel units based mostly on hydraulic and substrate features.

Lacustrine System

The lacustrine system consists of lakes, ponds, and reservoirs. Whole lakes are classified by geology, hydrology, and morphometry, and described by physical, chemical, and biological features. Lake zones are based on depth classes. Lake sites represent specific lake habitats based on substrate, flora, and other features.

Ground-Water System

Ground-water regions define patterns of aquifer systems with similar occurrence and availability of ground water. These regions are divided into hydrogeologic settings that define associations of aquifers whose hydrogeologic factors affect ground-water movement. Aquifers within these settings are based on their geology, hydrology, and water quality. Aquifer zones distinguish recharge areas from discharge areas. Finally, aquifer sites delineate springs and sinks where the water table intersects the land surface.

Ecological Classification Principles

This section discusses ecological and mapping principles that form the scientific basis for the classification and mapping of aquatic ecological units. These underlying principles are related to the aquatic hierarchy.

Nested and Networked Hierarchies

Hierarchical theory (Allen and Starr 1982, O'Neill *et al.* 1986) deals with multiscaled systems in which upper levels of organization provide the template from which lower levels emerge (Bourgeron and Jensen 1994). A major precept of hierarchical systems is that each component is a discrete functional entity and also part of a larger whole. Smaller systems develop within constraints set by the larger systems in which they are nested. This relationship is very useful in classifying and mapping aquatic systems and provides a basis for stratified sampling. Prediction of emergent properties in aquatic systems is greatly improved through an understanding of their hierarchical organization.

Watersheds, valley segments, stream reaches, and channel units are an example of hierarchical organization in riverine systems (Frissell *et al.* 1986, Minshall 1994). The geoclimatic features of a watershed constrain the types of valley segments of the stream network. Valley segment types constrain the stream reaches. Pool-riffle (channel unit) morphology is affected by stream reach type and the sediment and water input from the watershed (Schumm and Lichty 1965). These physical habitats and their biota control the form and function of aquatic communities (Frissell *et al.* 1986).

Networked hierarchies recognize that ecological units can have very similar patterns and processes among diverse geoclimatic and zoogeographic settings. For example, two streams with similar channel morphology can exist on diverse continents and yet exhibit similar fluvial characteristics (Montgomery and Buffington 1993,

Rosgen 1994). This fact also enhances classification, sampling, and extrapolation of information.

Pattern Recognition

Ecosystems are patterns of rather homogeneous units (Forman and Godron 1986, Urban *et al.* 1987). To analyze ecosystems, we must identify these patterns and their causes at various scales (Turner 1989). Ecological inventories must address three agents of pattern formation (Levin 1978, Urban *et al.* 1987): physical landscape features (biophysical environments); disturbance events (floods, droughts, etc.); and biotic processes (migration, extinction, etc.). Ecological relations are defined by matching patterns with their relevant agents of formation at appropriate spatial and temporal scales (fig. 2).

Classification of aquatic systems should help describe aquatic patterns and address the role of specific agents of pattern formation. Classification should also stress effects of biophysical environments and disturbance events on biological systems and the role of spatio-temporal scales in understanding these phenomena (Frissell *et al.* 1986, Minshall 1994, Poff and Ward 1990).

For example, inventories of riverine systems may describe changes in pattern from the channel unit to river basin scales (fig. 2a). Each scale spans a spatial and temporal range that reflects the key agents of pattern formation. This fact is vital to successful design and interpretation of ecological aquatic inventories.

Physical landscape features are the basic template on which aquatic patterns are formed. At coarse scales, ecoregion and river basin patterns respond to regional climate and physiography, which change over thousands to millions of years (fig. 2b). At medium scales, valley segments and stream reaches reflect variations in geomorphology and mesoclimate. At fine scales, channel unit patterns respond to variations in features such as substrate size and woody debris, which change over periods of months to years (Frissell *et al.* 1986).

Disturbance events affect aquatic pattern and occur at scales ranging from millimeters and minutes to hundreds of kilometers and millions of years (fig. 2c). Fine-scale events such as channel scour occur frequently and affect small habitats. Coarse-scale events such as regional floods and tectonic events occur less often and affect broad patterns such as valley segments **and** all the smaller patterns within them (Frissell *et al.* 1986, Minshall 1994).

Biotic processes also follow space-time scale relations (fig. 2d). Major geologic and climatic events such as tectonics and glaciation form watershed boundaries that isolate populations and create zoogeographic patterns through speciation and extinction over long time periods. Hydrologic events that recur from years to decades drive population dynamics between evolutionary (many generations) and ecological (few generations) time. Changes in water flow and quality at diel to annual cycles control behavior patterns (Poff and Ward 1990).

Physical features, disturbance events, and biotic processes are hierarchically related. Disturbance events affect habitat form and ecological function. The degree and spatial scale of such effects, and the force needed to alter physical features at different spatial scales, depend on the magnitude and frequency of events. The recovery time of an aquatic system following disturbance is related to the spatial scale and intensity of the event (Minshall 1994, Poff and Ward 1990). Landscape features and disturbance cycles form a physical habitat template that constrains species attributes as well as biotic processes, and responses in aquatic systems (Poff and Ward 1990).

Aquatic classification must reflect natural disturbance processes that express themselves as emergent properties of aquatic ecological units. Past disturbance regimes and the ecosystem patterns they maintained provide a template for assessing ecosystem health and diversity (Bourgeron and Jensen 1994, Swanson *et al.* 1994, Turner 1989). Correlating historic disturbance regimes with ecological units is vital to risk analyses (Hann *et al.* 1994), identification of restoration needs (Shlisky 1994), and resource planning and monitoring (Morrison 1994, O'Hara *et al.* 1994).

Driving Variables

Ecosystems exist at spatial scales ranging from global to microscopic. They may be defined by associations of ecological factors such as climate, geology, landform, soil, water, plants, and animals (USDA 1993). The association of all

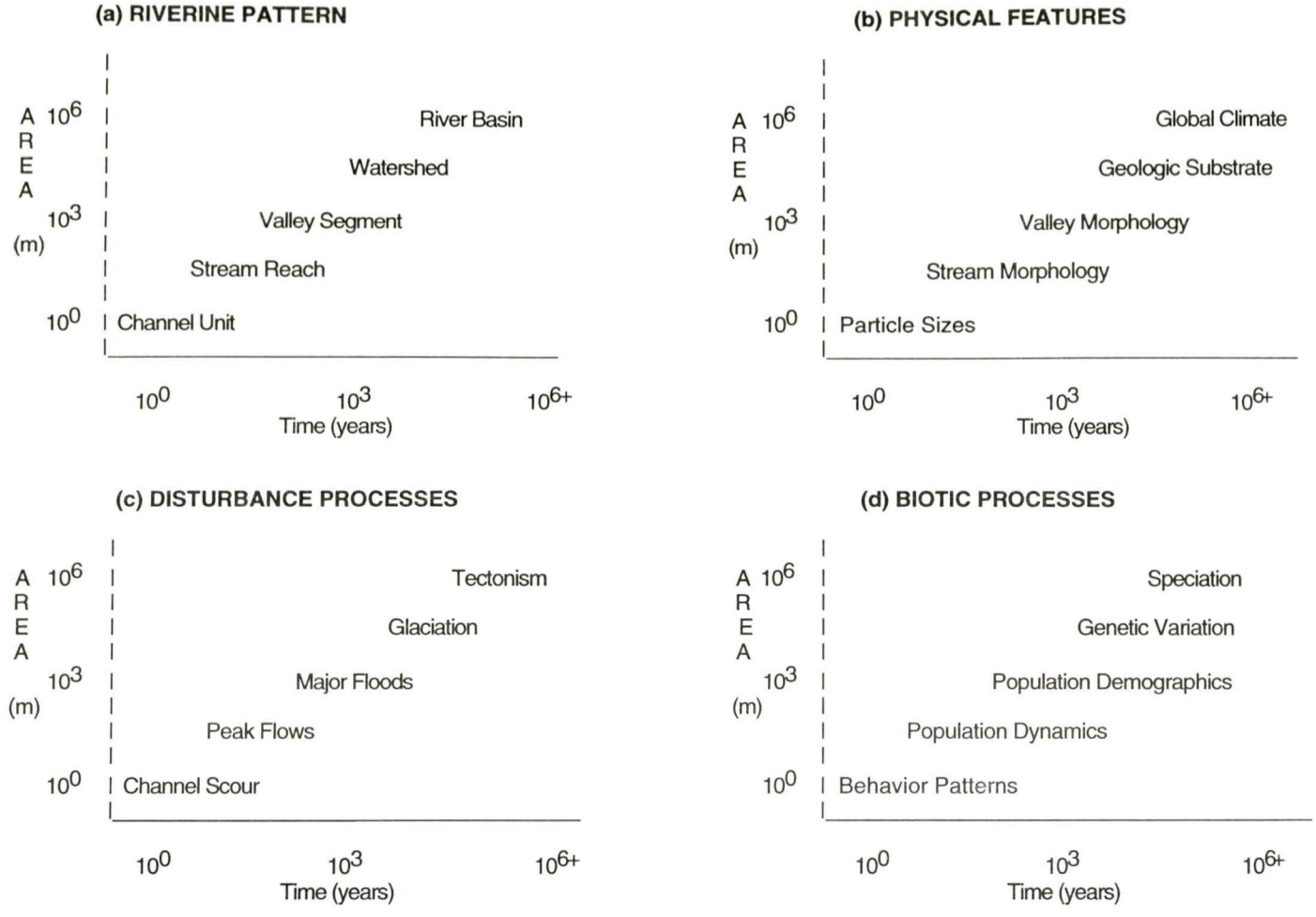


Figure 2.--Spatio-temporal scaled patterns of riverine systems (a). These patterns are created by physical features (b) and disturbance processes (c), and directly influence the biotic processes (d) that occur in riverine systems. Spatial and temporal scales shown are approximations of relations that will vary regionally.

factors is important in understanding ecosystems. However, the difficulty in classifying and mapping ecosystems is to identify those few variables that strongly affect ecological patterns and processes at various spatial scales. To be most effective, the driving variables used to classify and map aquatic systems at any scale should:

1. Dominate aquatic ecological processes.
2. Define classes that show similarities in pattern.
3. Distinguish classes based on the causes of class differences, not their effects (Strahler 1975).
4. Display a high degree of covariance with other important ecological attributes.
5. Reflect nested and networked hierarchical constraints.
6. Be easily mappable.

The number of variables used in classification and mapping should be limited to promote efficient and consistent products that can be readily understood by users. This objective requires that the criteria listed above be used to identify the basic elements (Wertz and Arnold 1972) or controlling factors (Bailey *et al.* 1994) that most affect patterns and processes in aquatic systems. Because these factors change with scale (USDA 1993), a hierarchical, multifactor approach should be used to design ecological classifications and mapping units (Bailey *et al.* 1994, Rowe 1980).

This aquatic classification and mapping framework follows the ecological classification principles discussed above. Table 1 gives examples of riverine classification at various scales. Table 2 shows some relationships between map unit design criteria for terrestrial and aquatic ecological units.

GEOCLIMATIC SETTINGS

The National Hierarchical Framework of Ecological Units (USDA 1993) classifies and maps land systems (geoclimatic settings) based on associations of physical and biological factors that affect energy, moisture, and nutrient gradients that regulate the structure and function of ecosystems. Map units exhibit similar patterns of climate, geology, and landform that affect soil and vegetation patterns and their many ecological processes. Classifications used to construct this hierarchy include those of Fenneman (1938a, 1938b), Wertz and Arnold (1972), Bailey (1989), and Omernik (1987).

Domains, divisions, and provinces are defined mainly by global, continental, and regional climatic regimes. Sections, subsections, and landtype associations are identified chiefly by geology and geomorphology. Landtypes and landtype phases are defined primarily by landform, soil, and vegetation patterns.

This geoclimatic template defines patterns of aquatic systems, water chemistry, and hydrologic regimes that affect the form and function of watersheds and their aquatic systems (Platts 1979). Climate, geology, and geomorphology are the prime driving variables that govern fluvial processes in watersheds (Lotspeich 1980), the water quality and structure of aquatic habitats (Omernik 1987), and aquatic population distributions within river basins (Minshall 1994, Naiman *et al.* 1987, Perry and Schaeffer 1987).

Geoclimatic settings serve two primary purposes in characterizing aquatic environments. They are used to group watersheds into similar types based on their structure and function, which improves watershed analysis, management, and monitoring. They are also used to define patterns of finer scale aquatic systems within watersheds, which helps us classify and describe these systems. The remainder of this section discusses these two uses of geoclimatic settings.

Geoclimatic Settings and Watersheds

Watersheds can be characterized and assessed on the basis of the geoclimatic setting in which they are found. The transport of water, sediment, and solutes is governed by geoclimatic factors such as elevation, relief, slopes, landforms, soils, drainage density, and plant cover. Because land systems distinguish important hydrogeomorphic properties of a watershed, they are very useful in grouping watersheds into types with similar hydrologic responses.

Table 1.—*Examples of riverine characterization at different hierarchical scales*

Mapping scale	Riverine patterns	Physical features	Disturbance processes	Biotic processes	Approx. time for change/years
1:2,000,000 +	Subzones to Subbasins	Basin boundaries River networks Regional climate Regional geology	Tectonics Glacial cycles	Speciation/extinction	>10,000
1:100,000	Watersheds Subwatersheds	Watershed boundaries Stream networks Geomorphology Local climate	Local uplift Folding/faulting Flood cycles	Genetic variation	1,000-10,000
1:24,000	Valley segments	Valley geomorphology Climatic regime Hydrologic regime	Valley filling Channel migration Stream incision	Population demographics	100-1,000
1:12,000	Stream reaches	Channel morphology Bed form/materials Bank conditions Woody debris	Peak flows Sediment transport	Population dynamics	10-100
1:1,000	Channel units	Habitat features Depth patterns Debris patterns	Hydraulics Scour and deposition Bedload sorting	Behavior patterns	1-10

Table 2.—*Abbreviated principal map unit design criteria for ecological units*[1]

Terrestrial Units and criteria (USDA 1993)	**Aquatic Units and criteria**
• DOMAINS = sub-continental climate zones (humid, dry, tropical)	• SUBZONES = fish family patterns
• DIVISIONS = regional climate zones (Köppen 1931, Trewartha 1968)	• REGIONS = fish community patterns
• PROVINCES = potential natural vegetation zones (Küchler 1964)	• SUBREGIONS = fish community subpatterns
• SECTIONS = climatic, lithologic, and landform groups	• RIVER BASINS = fish species assemblages (endemism)
• SUBSECTIONS = general lithology and geomorphology	• SUBBASINS = physiography and species groups
• LANDTYPE ASSOCIATIONS = specific lithology and geomorphology	• WATERSHEDS = hydrography and fish genetics
• LANDTYPE = specific lithology, landform, soils, and potential natural vegetation	• SUBWATERSHEDS = hydrography and fish genetics
• LANDTYPE PHASE = site-specific patterns of soils and potential natural vegetation	• VALLEY SEGMENTS & LAKES = geomorphology, climatic regime, and hydrologic regime
• SITES = micro-environments	• STREAM REACHES & LAKE ZONES = channel and lake morphology
	• CHANNEL UNITS & LAKE SITES = site-specific habitat features (hydraulics, substrate, etc.)

[1] *The criteria listed are broad categories of environmental and landscape components. The actual classes of components chosen for designing map units depend on the objectives for the map.*

Understanding the relationships that exist between land and aquatic systems is key to predicting their response to natural or human-induced disturbances. For example, predicting effects of mass erosion on sediment delivery to streams and sediment routing downstream to critical fish habitat commonly requires knowledge of the nature and interrelationships of the landtype associations, land types, stream networks, and valley segments that occur in the area.

Geoclimatic settings such as subsections and landtype associations are used to group watersheds based on geomorphic structure and overall hydrologic response. The mix of specific criteria used to stratify watersheds, however, must be governed by local climate, geology, topography, and plant cover (Minshall 1994) and by specific ecosystem management needs. The geoclimatic setting that immediately encompasses the watershed defines the context of the watershed. Similar geoclimatic settings would identify similar watershed types.

Geoclimatic patterns such as landtypes divide the watershed into meaningful hydrologic response units and help us understand the functional components of the watershed. Infiltration and evapotranspiration, runoff and erosion, and surface and subsurface flow systems are influenced by the properties of land units.

Geoclimatic Settings and Aquatic Systems

Ecological linkages between land and aquatic systems are very important. By understanding these linkages, we can analyze attributes of aquatic systems together with the climate, geology, and landform attributes of the land units within which they are nested. Land units define the geoclimatic context of aquatic units.

These linkages apply at all hierarchical levels. Very large lakes and aquifers are nested within vast geoclimatic settings such as provinces and sections, whose features help describe them and assign them to similar classes. Subwatersheds and stream networks are nested within mesoscale landscapes such as subsections and landtype associations. At finer scales, stream reaches and most lakes are nested within landtypes and landtype phases, whose attributes may be used to help predict the stream and lake classes likely to be found within them. Valley segment settings may be used to predict stream reach types likely to be nested within them.

Since the ecoregion maps of Bailey (1983) and Omernik (1987) both utilize geoclimatic settings as defining criteria, there should be some correlation between these ecoregions and fish distributions at the landscape level. Indeed, Hughes *et al.* (1990) have shown a coarse-scale correlation between ecoregions and fish distributions over widely separated geographic areas of the United States. However, both Lyons (1989) and Poff and Allan (1995) have suggested that an understanding of fish assemblages and distributions within ecoregions is improved considerably by using habitat variables and hydrology, respectively. Moreover, Bayley and Li (1992) have explained that some of the inconsistency of ecoregions in predicting fish distributions can be attributed to the fact that the ecological potential of aquatic ecosystems may be dominated by geoclimatic conditions in the headwaters of their watersheds and not by the ecoregion in which they occur. The following sections describe how hydrologic units and geoclimatic settings can be used together to rigorously define fish distributions and their general habitats.

ZOOGEOGRAPHIC SETTINGS

Two factors make watersheds a valid choice for ecological classification of surface-water systems within geoclimatic settings. First, watersheds provide a natural nested hierarchy for ecological stratification and analysis over a wide range of scales (Hornbeck and Swank 1992, Lotspeich 1980, Odum 1971). Second, watersheds integrate many physical, chemical, and biological processes affecting the form and function of both aquatic and terrestrial ecosystems. This effect is related to lithology and geomorphic surfaces created by geoclimatic processes.

For the most part, watersheds are distinct geomorphic units bounded by drainage divides. Exceptions occur when subsurface geology or low surface relief promotes ground-water or flood-water transfers between watersheds, respectively. These exceptions do not detract from the utility of watersheds as suggested by Hughes and Omernik (1981) as long as these processes are recognized.

The geoclimatic processes that created watershed divides and that distinguish physiographic patterns of watersheds are also responsible for the distribution of many native aquatic organisms. This is especially true of mussels and fish whose entire life cycles are confined to water, but may not fully apply to some aquatic plants and insects whose life cycles are affected by wind. The zoogeographic outcomes of geoclimatic processes may be arranged in a hierarchical structure using the emergent properties of biological systems.

For example, unique assemblages of aquatic communities reflect, and can be used to delineate, the geoclimatic impact on large regions. At middle levels of the hierarchy, unique aquatic communities are less distinct and are recognized more by the presence of unique species or endemism. At lower hierarchical levels, endemism is still important, but relationships between physiography and species groups predominate and intra-species genetics become important.

Darlington (1957) has proposed six zoogeographic zones of the world. They are the **Nearctic** (North America), **Neotropical** (South and Central America), **African** (Africa), **Oriental** (India, Southeast Asia, Macronesia), **Palaearctic** (Eurasia north of the Oriental zone), and **Australian** (Australia, New Zealand, New Guinea).

For the Nearctic zone, fish zoogeography has been described by Hocutt and Wiley (1986), Hubbs *et al.* (1974), Lee *et al.* (1980), Mayden (1992), Miller (1959), and Moyle and Cech (1988). Mussel zoogeography has been addressed by Williams *et al.* (1993). The Nearctic zone has 950 to 979 native fish species and 297 known taxa of freshwater mussels. By consulting the above references and various ichthyologists, we have subdivided the Nearctic zone into seven hierarchical levels. The first three divisions are depicted in figure 3 and table 3.

Subzones

The Pacific, Arctic-Atlantic, and Mexican Transition Aquatic Subzones are subcontinental zoogeographic strata with unique aquatic communities, created in large part by plate tectonics and mountain building. Eastern and western North America have had quite independent faunal histories since the pre-Pliocene uplift of the Rocky Mountains (Gilbert 1976). Fish fauna of the Arctic-Atlantic Subzone are widely distributed, those of the Pacific Subzone have experienced restriction and increased endemism, and those of the Mexican Transition Subzone reflect both expansion (mainly in the south) and restriction (mainly in the north).

Table 3.—*Aquatic subzones, regions, and subregions in the nearctic zone (North America). The alphanumeric coding is cross referenced to figure 3.*

SUBZONE	REGION	SUBREGION
Pacific (P)	Coastal (P1)	North Coastal (P1a)
		Columbia Glaciated (P1b)
		Columbia Unglaciated (P1c)
		Upper Snake (P1d)
		Mid-coastal (P1e)
		Central Valley (P1f)
		South Coastal (P1g)
	Great Basin (P2)	Bonneville (P2a)
		Lahontan (P2b)
		Oregon Lakes (P2c)
		Death Valley (P2d)
	Colorado (P3)	Upper Colorado (P3a)
		Little Colorado (P3b)
		Vegas-Virgin (P3c)
		Gila (P3d)
		Lower Colorado (P3e)
Arctic-Atlantic (A)	Rio Grande (A1)	Upper Rio Grande (A1a)
		Guzman (A1b)
		Conchos (A1c)
		Pecos (A1d)
		Mapimi (A1e)
		Lower Rio Grande (A1f)
	Mississippi (A2)	Upper Mississippi (A2a)
		Middle Mississippi (A2b)
		Mississippi Embayment (A2c)
		Upper Missouri (A2d)
		Middle Missouri (A2e)
		Central Prairie (A2f)
		Interior Highlands (A2g)
		Southern Plains (A2h)
		East Texas Gulf (A2i)
		West Texas Gulf (A2j)
		Teays (A2k)
		Old Ohio (A2l)
		Tennessee-Cumberland (A2m)
		Mobile Bay (A2n)
		Florida Gulf (A2o)

(table 3 continued on next column)

(table 3 continued)

SUBZONE	REGION	SUBREGION
	Atlantic (A3)	Florida (A3a)
		South Atlantic (A3b)
		Pamlico-Albemarle Sound (A3c)
		Chesapeake Bay (A3d)
		Long Island Sound (A3e)
		Gulf of Maine (A3f)
	St. Lawrence (A4)	Superior (A4a)
		Michigan-Huron (A4b)
		Erie-Ontario (A4c)
		Lower St. Lawrence (A4d)
		North Atlantic-Ungava (A4e)
	Hudson Bay (A5)	Upper Saskatchewan (A5a)
		Lower Saskatchewan (A5b)
		English-Winnepeg Lakes (A5c)
		Circum-Hudson (A5d)
	Arctic (A6)	Gulf of Alaska (A6a)
		Yukon (A6b)
		Upper Mackenzie (A6c)
		Lower Mackenzie (A6d)
		East Arctic (A6e)
		Arctic Islands (A6f)
Mexican Transition (M)	Central Plateau (M1)	
	Pacific Coastal (M2)	
	Gulf Coastal (M3)	

Uses

This level of the hierarchy has broad applicability for modeling and sampling. Aquatic subzones also can be used to address questions of strategic international and intergovernmental planning and assessment.

Map Unit Delineation and Scale

Hydrologic units are aggregated into subzones covering millions of square kilometers. Mapping scale is 1:7,500,000.

Defining Criteria

Broad patterns of fish families and unique aquatic communities define subzones. Major faunal elements in the Pacific Subzone include distinctive cyprinid and catostomid genera and species of the families Salmonidae, Cyprinodontidae, and Cottidae. Much of the Arctic-Atlantic fauna include species of Cyprinidae, Percidae, Centrarchidae, and Ictaluridae (Mayden 1992).

The Mexican Transition Subzone is the southern limit of seven North American families, the northern limit of two South American families, and the seat of evolution of one family.

Regions

Regions portray refinements of fish distributions resulting from changes in routes of dispersal and isolation within subzones caused by geoclimatic factors. Barriers to dispersal caused by glaciers, or changes in flow patterns caused by uplift after and subsidiary to that separating subzones, are the major agents for this delineation.

Uses

This level has broad applicability for regional modeling and sampling, and for addressing questions of strategic regional interagency planning and assessment.

Map Unit Delineation and Scale

Hydrologic units are aggregated into regions covering hundreds of thousands of square kilometers. Mapping scale is 1:7,500,000.

Defining Criteria

Patterns of unique communities, endemism, and dispersal within fish families define regions. For example, fault-block uplift separated the Pacific Coast, Great Basin, and Colorado regions of the Pacific Subzone and created their distinct communities. The six Arctic-Atlantic regions mostly reflect mergings and separations of fish caused by Pleistocene glaciations and Appalachian orogeny. The three regions of the Mexican Transition Subzone separate the central plateau with high endemism from the two coastal regions that were likely dispersal routes for fishes coming from both north and south.

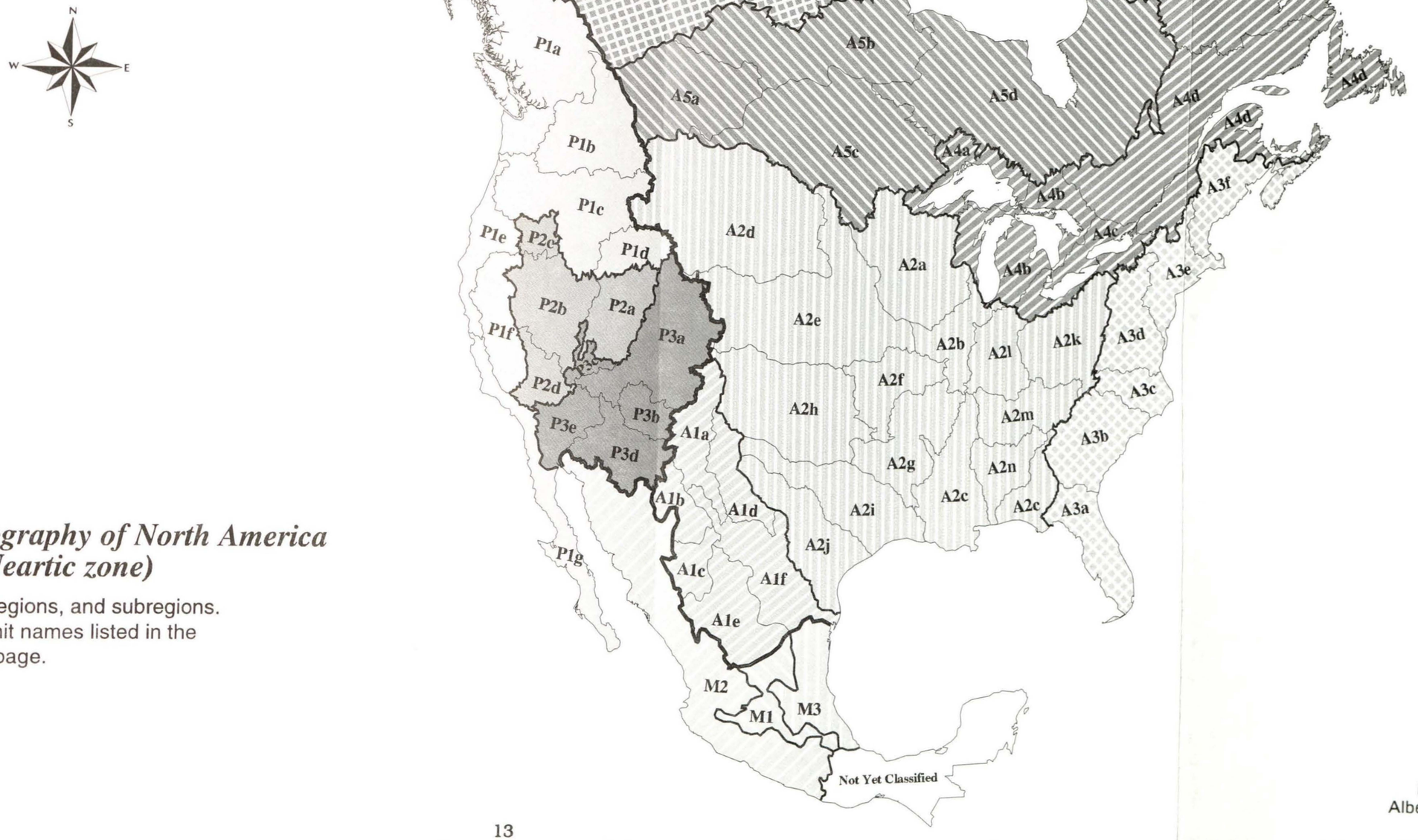
Subregions

Aquatic subregions are major drainage systems within a region that are defined by endemism and unique fish communities. Subregions reflect further refinement of fish similarity indices, but the fauna within each subregion show some common ancestry to others within the region. Historic mixing and isolation of stream patterns within regions created the population distributions of subregions.

Figure 3:

Aquatic Zoogeography of North America (Neartic zone)

Depicting subzones, regions, and subregions.
Labels refer to map unit names listed in the
table on the previous page.



USDA Forest Service
Rocky Mountain Region
Geometronics group
Map scale 1:27,500,000
Albers Equal-area projection

Uses

This level has broad applicability for subregional modeling and sampling, and for questions of strategic subregional interagency planning and assessment.

Map Unit Delineation and Scale

Hydrologic units are aggregated into subregions covering tens of thousands to hundreds of thousands of square kilometers. Mapping scale is 1:7,500,000.

Defining Criteria

Subregions are defined by major drainage systems whose geomorphic history caused the mixing and isolation of fish species. For example, during Pliocene times in the Mississippi Region, the present Missouri River flowed north into the Hudson system, and the "Plains" River (analogous to much of the present Arkansas, Red, and White Rivers) flowed south into the Gulf of Mexico without connecting to the Mississippi. This allowed unique faunal elements to develop. Pleistocene events connected these waters to the Mississippi River system and modified their faunal relationships, which resulted in the present pattern of subregions in the Mississippi Region (table 3).

River Basins

River basins are parts of a subregion with clear hydrographic boundaries that have been isolated from each other long enough to show some differences in fish species. In many cases, adjoining basins have high similarity indices, but the presence of unique or endemic species is the basis for their delineation. The identification of all basins in North America is incomplete as of the time of this writing.

Uses

This level of the hierarchy can be used for strategic statewide and multiagency analysis and assessment.

Map Unit Delineation and Scale

Hydrologic units are aggregated into basins covering thousands to tens of thousands of square kilometers. Mapping scale is 1:2,000,000.

Defining Criteria

River basins are defined by the presence of unique species assemblages, and often one or more endemic aquatic species, caused by the formation of discrete river systems with clear hydrographic divides. Each basin's geoclimatic history created barriers to dispersal through isolation caused by climate change, oceans, or hydrographic divides.

Aquatic Zoogeography Within River Basins

Both hydrologic units and geoclimatic patterns segregate aquatic populations (Moyle and Ellison 1991). Basins may be divided into ***subbasins*** based on physiographic criteria that define different physical-chemical habitat patterns inhabited by distinct species groups (fig. 4). Species are further grouped by physical and chemical habitat patterns within stream and lake systems (Moyle and Cech 1988). Subbasins are typically thousands of square kilometers in size.

Subbasins are divided into ***watersheds*** and ***subwatersheds*** using hydrographic criteria (Appendix A). Clusters of these smaller hydrologic units often separate genetic groups within species. For example, Perkins *et al.* (1993) show that brook trout in New York stratify genetically by watersheds; they suggest that defining heterozygosity in polymorphic loci is vital to preserving heritage populations in a watershed hierarchy. Similar patterns have been documented for walleye (Billington and Hebert 1988), chinook salmon (Bartley and Gall 1990), and yellow perch (Todd and Hatcher 1993). This genetic data can be attributed to individual watersheds, streams, and lakes. Watersheds and subwatersheds are hundreds and tens of square kilometers in size, respectively.

In summary, defining patterns of aquatic communities and speciation from the subzone to river basin levels is critical to assessing aquatic biodiversity and native species distributions. At the subbasin level and below, knowledge of geoclimatic and habitat patterns and genetic variation within species is crucial to sound fisheries management programs that recognize population diversity both among watersheds (species) and within watersheds (stocks). Zoogeographic information can be attributed to watersheds, subwatersheds, valley segments, and lakes as one progresses through this hierarchy.

Watershed Characterization

Watersheds at any scale exhibit certain biophysical characteristics that are determined by their geoclimatic and zoogeographic settings and their morphologic features. Watershed patterns can be defined from similarities in settings and features using four major types of information:

1. The **geoclimatic** pattern of a watershed is defined mostly by climate and physiography (USDA 1993). This pattern governs aquatic system structures, water chemistry, and hydrologic regimes that control the form and function of watersheds (Minshall 1994). The landscape (subsection, landtype association) that engulfs the watershed defines the watershed's geoclimatic setting. Land units (landtypes) within a watershed stratify the watershed into hydrologic response units that explain pattern and process variation.

2. The **zoogeographic** pattern of a watershed is defined by distributions of aquatic biota. Aquatic zoogeography is critical to assessing native species distributions and aquatic biodiversity. Aquatic zoogeography of subbasins defines the zoogeographic setting of whole watersheds. Geoclimatic patterns and intra-species genetics define zoogeographic patterns within watersheds.

3. The **morphology** of the watershed and its stream network is governed by geoclimatic factors and is used to quantify geoclimatic watershed patterns. Watershed morphology affects hydrologic processes such as water and sediment yield, flow durations, and magnitude and frequency of floods.

4. The **disturbance** history of a watershed allows it to be placed into disturbance classes for analyzing effects. This history includes natural events such as fires, floods, and pestilences as well as human impacts such as roads, timber harvest, and grazing.

Watershed features control water, sediment, and nutrient cycling in aquatic systems (Hornbeck and Swank 1992). Watershed patterns are used to assess hydrogeomorphic processes and aquatic ecosystem structure and function for distinct landscapes. Uses of such watershed patterns include:

1. Assessment of aquatic biodiversity and native species distributions at the subbasin, watershed, and finer scales (Bartley and Gall 1990, Billington and Hebert 1988, Perkins *et al.* 1993, Todd and Hatcher 1993).

2. Prediction of streamflow, sediment, and thermal regimes, including water and sediment yield, peak and base flows, and flow durations (Kircher *et al.* 1985, Marston 1978, Maxwell and Marston 1980).

3. Characterization of surface-water and ground-water quality and fish habitat, since physiography affects aquatic habitat structure (Heller *et al.* 1983), nutrient availability, and water chemistry.

4. Watershed analysis and monitoring, since watershed and water body health should be diagnosed and compared among watersheds with similar geoclimatic characteristics and ecological potentials (Ohlander 1993).

5. Data storage and analysis, since information derived for stream reaches and lakes is aggregated by hydrologic units (Seaber *et al.* 1987).

The geoclimatic and zoogeographic settings of aquatic systems are vital to assessing their interacting forms, functions, and processes. These settings and their nested aquatic systems function and respond to disturbances together. Linking them within a Geographic Information System will improve integrated (ecological) analysis and management of watersheds and their aquatic and riparian systems.

The U.S. Geological Survey (USGS) has mapped four levels of hydrologic units in the United States (Seaber *et al.* 1987). These units are based on physical size criteria. Each level of hydrologic units in this paper follows lines already mapped by the USGS. However, the pattern of hierarchical levels is different since it is based on geoclimatic and zoogeographic criteria. Hydrologic units at all scales must be viewed in the context of their geoclimatic and zoogeographic settings. Appendix A gives guidelines for mapping hydrologic units, and contains a list of geomorphic parameters related to watershed form and function.

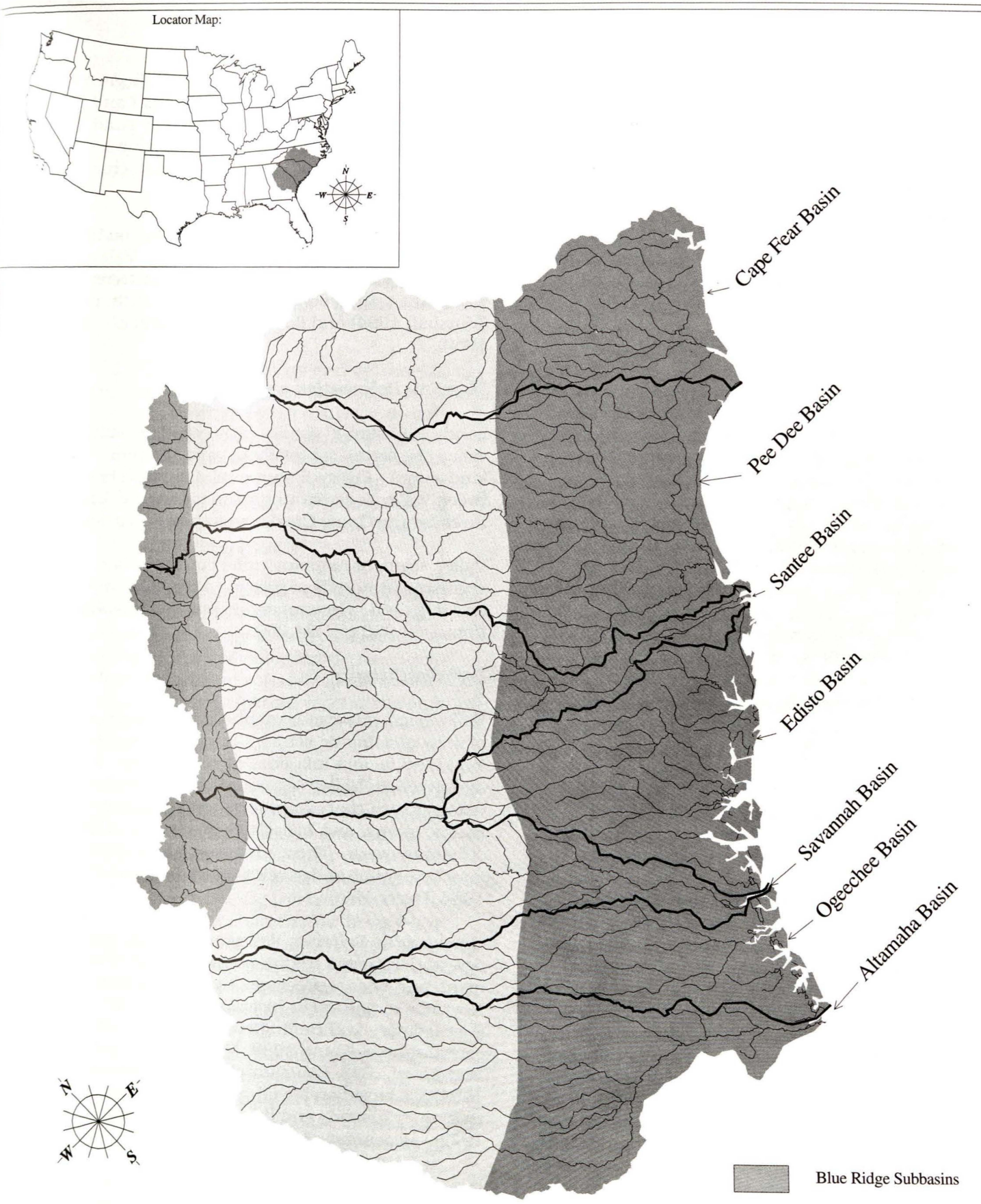


FIGURE 4. Subbasins of the South Atlantic Subregion. The Cape Fear through Altamaha basins are shown along with their Blue Ridge, Piedmont, and Coastal Plain subbasins.

THE RIVERINE SYSTEM

The riverine system consists of rivers and streams that form a stream network. Fluvial processes of the riverine system are primary mechanisms for landscape erosion and transport of sediments to the sea or a closed basin. The riverine system has three hierarchical levels nested within a subwatershed and its stream network (Parrott *et al.* 1989): valley segments, stream reaches, and channel units.

Valley Segments

Valley segments stratify the stream network into major functional components that define broad similarities in fluvial processes, sediment transport regimes, and riparian interactions. A limited set of stream reaches is nested within any given valley segment. Segments often break at stream junctions, slope breaks, and changes in adjacent geoclimatic land units (USDA 1993), which may help define valley segments. Examples of valley segment classification appear in Frissell *et al.* (1986), Cupp (1989), Paustian *et al.* (1992), Montgomery and Buffington (1993), and Rosgen (1994). Stream chemistry and biotic composition are descriptive data attributes attached to mapped valley segments.

Uses

Valley segments are used to assess hydrology, fluvial processes, and aquatic habitat and riparian vegetation patterns for major portions of a stream network. Segment classes are useful for analyzing long-term, large-scale fluvial response to a major disturbance. Examples include major channel changes due to upstream sediment inputs, and channel response to increased or decreased streamflow caused by water diversions or vegetation manipulation (Montgomery and Buffington 1993).

The relationship between valley segments and adjacent geomorphic surfaces can also have a strong influence on surface hydrology. Valley segment classes are useful in defining important hydrologic linkages between aquatic and terrestrial units such as storm flow source areas and low flow recharge zones (Brinson 1993, Winkler and Rothwell 1983).

Riparian vegetation patterns are closely linked to stream channel morphology and adjacent fluvial geomorphic surfaces (Harris 1988, Hawk and Zoebel 1974, Naiman *et al.* 1992). Segment classes are useful in assessing the extent and frequency of overbank flooding. Flooding and associated soil and nutrient accretion play a major role in shaping riparian vegetation characteristics (Brinson 1993).

Valley segments provide general insights on habitat capability and use by aquatic biota. Valley segment classes define gross habitat patterns within the spatial context of the river continuum (Minshall 1994) and floodplains (Junk *et al.* 1989).

Map Unit Delineation and Scale

Land units should consistently correlate with valley segments, especially in valley bottom landscapes. Figure 5 shows relationships between valley segment units and landscape features for the Game Creek watershed in Alaska.

Valley segment mapping units consist of line segments hundreds of meters to tens of kilometers in length. Recommended map scale ranges from 1:63,000 to 1:24,000.

Defining Criteria

Valley segments can be defined within the context of their geoclimatic setting. Such large-scale, long-term factors influence stream genesis, form, and process. Valley segments can be classified by using criteria that describe general geomorphic, hydroclimatic, and hydrologic processes within a stream network. These processes also explain aquatic habitat and species patterns (Nelson *et al.* 1992, Platts 1979).

Geomorphic Criteria: Valley morphology, geology, and adjacent landforms govern flow, sediment, and energy processes that affect channel response to natural or human disturbances (Montgomery and Buffington 1993). Most stream classifications (Cupp 1989, Montgomery and Buffington 1993, Paustian *et al.* 1992, Rosgen 1994) are based on fluvial process concepts of erosion, transport, and deposition (Schumm 1977). Recommended criteria include:

1. *Confinement*: Valley floor width divided by bankfull channel width is a useful index of sediment source, delivery, storage, and floodplain processes associated with a given valley segment (Montgomery and Buffington 1993).

2. *Slope*: Valley slope expresses key geomorphic properties of associated valley segments (Hack 1957, Wheeler 1979). Collotzi (1974) used slope classes to define valley bottom types useful for making riparian and aquatic resource interpretations. Valley slope is measured on topographic maps as segment relief divided by segment length (Hack 1957). Plots of channel profiles often help identify segment breaks and base level controls.

3. *Geology*: Lithology and geomorphology identify the nature and origin of materials through which a stream flows. Lithology and surface materials influence stream substrate composition (Hack 1957), hydrologic and chemical regimes (Walton 1970), and surface-ground water interactions (Bugliosi 1988, Siegel 1989).

Hydroclimatic Criteria: Certain segment features related to watershed and stream network morphology strongly influence flow and thermal regimes of valley segments. Such factors often define aquatic habitat and species distributions and riparian vegetation communities within subwatersheds. Recommended criteria include:

1. *Climate*: Hydrology and water temperature of valley segments are strongly affected by elevation and aspect. For example, rain-on-snow runoff from transient snow zones can augment peak flows, while fog interception in coastal zones can augment low flows (Harr 1983, 1986). Thermal regime is useful for inferring potential riparian vegetation, rates of ecological processes, and distributions of aquatic biota.

2. *Stream Size*: Stream order (Strahler 1957) and link number (Shreve 1966) identify the position and the relative scale of the segment in the stream network. Stream order is commonly used for morphometric analysis of watersheds; link number correlates with stream discharge and stream power (Gregory and Walling 1973).

Hydrologic Criteria: The permanence, source, and ground-water linkage of streamflow are three components of hydrologic regime. Recommended criteria include:

1. *Flow Regime:* Habitat quality and the biotic productivity and diversity of aquatic and riparian ecosystems increase from ephemeral to intermittent to perennial streams. The flow regime defines patterns of fluvial process and biotic potential in a stream network.

2. *Water Source*: The source of water defines hydrologic and water quality features of valley segments. For example, channel form, habitat structure, water quality, and biotic makeup of glacier-fed streams differ sharply from those of non-glacial streams (Murphy *et al.* 1989, Sidle and Milner 1990). Streams draining large peatlands also have distinct hydrographs, ground-water linkages, and nutrient budgets (Verry and Boelter 1978). Hydrologic regimes are also affected by tides, spring systems, and lake outflows.

3. *Ground-Water Linkage*: As a source of water, ground water can influence a streams flow, chemical, and thermal regimes. A stream is considered as gaining (ground-water discharge prevails), losing (ground-water recharge prevails), or unlinked to ground water (surface sources prevail).

Valley segments are relatively coarse strata of the stream network, so they are more variable than stream reaches or channel units. This hierarchical level is most useful for landscape-scale analysis. The mix of defining criteria and the weight given to each will vary regionally with the hydrogeomorphic processes at work in a watershed and with the ecosystem management issues at hand. Mapping can be done using topographic maps and aerial photographs.

Stream Reaches

The stream reach is a subdivision of the valley segment that defines patterns of channel units. Stream reach classes have a high degree of uniformity in channel morphology and flow. They describe and integrate a consistent range of physical and biological interactions including

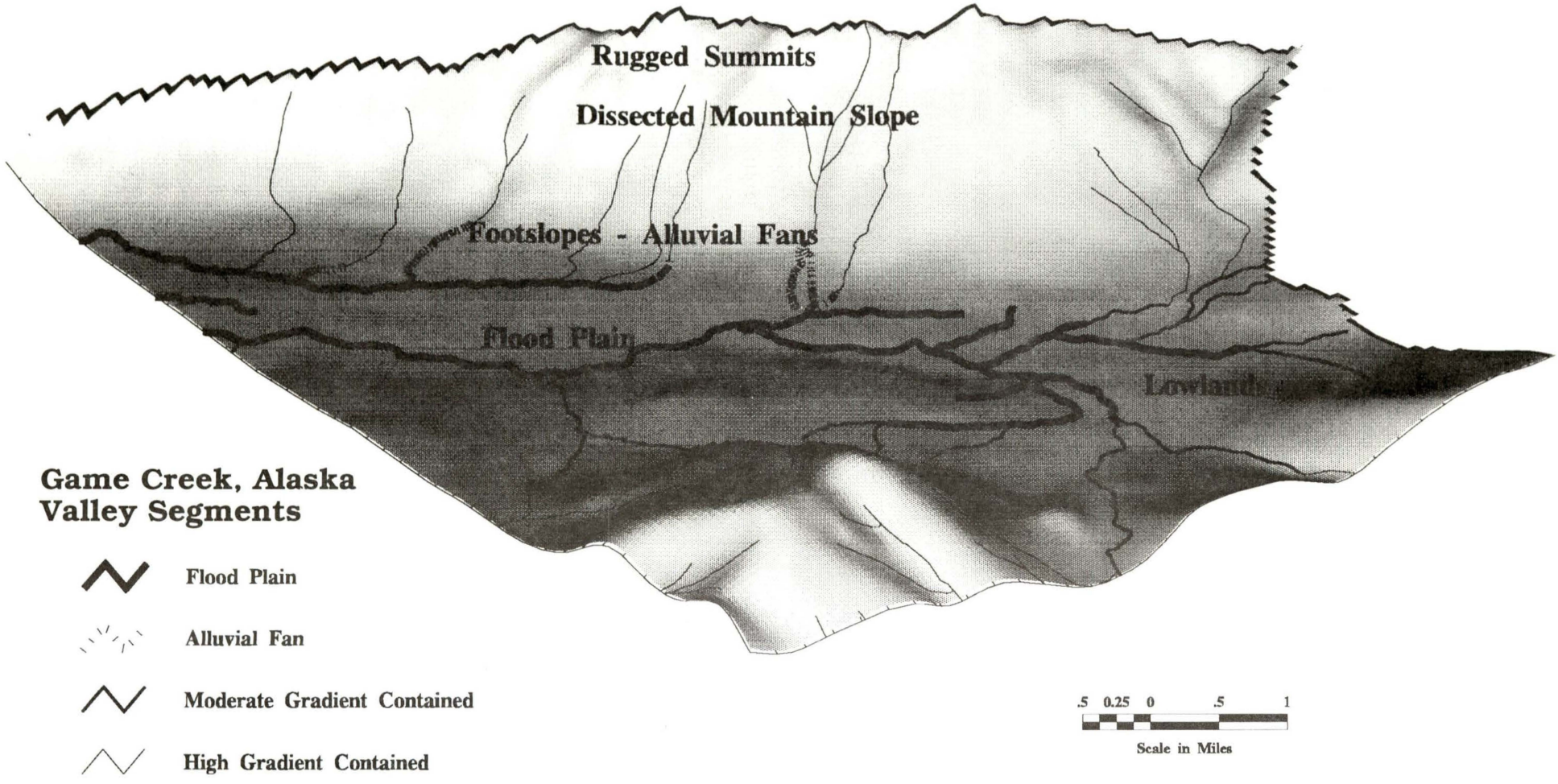


Figure 5.—*Valley segments and land units for Game Creek watershed, Alaska.*

fluvial processes, riparian processes, and aquatic habitat structure and function. Adjoining land units or landforms that control fluvial processes should be used to help define stream reaches based on their geomorphic properties.

Uses

Stream reach classification is useful for predicting local stream response to perturbation (Montgomery and Buffington 1993, Rosgen 1994). For example, a low gradient alluvial channel will respond to increased sediment loads with channel widening and bed aggradation, while a steep bedrock channel will be rather insensitive to increased sediment loads.

Reach classes are useful in assessing aquatic habitat quality. Habitat quality can be linked to aquatic productivity if populations are limited by habitat more than factors such as fish interception, recent floods, and species competition (Fausch *et al.* 1984). Stream reaches can be used to predict fish distributions (Edgington *et al.* 1987), patterns of habitat units (Bryant *et al.* 1991, Kershner *et al.* 1992, Murphy *et al.* 1987), and fish density (Lanka *et al.* 1987, Paustian *et al.* 1993, Thedinga *et al.* 1993).

Stream reach strata are useful for assessing stream health. Cumulative effects to aquatic habitat from depletion of large woody debris, changes in streamflow and sediment loads, chemical inputs, and stream bank erosion are best diagnosed at this level (Ohlander 1993).

Stream reaches have rather predictable patterns of riparian vegetation, whose structure and function are related to interactions of stream-adjacent landforms (Harris 1988, Hawk and Zoble 1974, West *et al.* 1989). Stream response to changes in aquatic trophic structure and thermal regime caused by riparian disturbance can be assessed with such patterns.

Stream reaches are well suited for cataloging site-specific information on the stream network. Stream reaches should be the basic strata for collection and storage of stream quality and fish population data. Site-specific features such as dispersal barriers can be mapped and attributed to stream reach units.

Map Unit Delineation and Scale

Reach map units encompass stream lengths of 100 meters to thousands of meters in length. Map unit delineations are made at the 1:24,000 to 1:12,000 scale.

As discussed earlier, valley segment breaks are delimited by major channel slope breaks, adjacent landform features, and stream confluences. Stream reaches are refinements of these segment breaks. Stream reach units are defined by changes in channel bedform, channel width, channel entrenchment, stream gradient, riparian vegetation pattern, or other fairly localized features. Boundaries of reach map units should be verified in the field.

Defining Criteria

Most existing stream reach classifications rely on a common array of geomorphic factors to define stream reaches (Frissell *et al.* 1986, Montgomery and Buffington 1993, Paustian *et al.* 1992, Rosgen 1994). Criteria recommended for classifying stream reach types include:

1. *Channel Pattern* is governed by geomorphic controls and sediment transport regimes. Single channels may have straight, sinuous, meandering, or tortuous patterns, while multiple channels may have braided or anastamosing patterns (Rosgen 1994). **Sinuosity** is the ratio of channel length to valley length.

2. *Channel Entrenchment* is a stream's vertical containment and degree of incision into the valley floor (Kellerhals *et al.* 1972). This criterion indicates how well floods are contained by a stream channel; it provides an index of the energy available to modify the channel and of the influence of channel sideslopes on sediment and debris delivery. Rosgen (1994) defines entrenchment ratio as flood-prone area width to bankfull channel width.

3. *Channel Width* is a prime indicator of flow volume and channel hydraulic conditions. Width of the bankfull channel is measured perpendicular to

the flow in a uniform reach. **Basin area** draining to a given stream reach may be a more accurate index of flow volume in disturbed watersheds (Ralph *et al.* 1994). **Width/depth ratio** is a dimensionless channel shape factor equal to bankfull channel width divided by bankfull mean depth. It reflects hydraulic geometry and sediment transport relations (Rosgen 1994) and bed and bank erosion processes (Osborn and Stypula 1987).

4. *Channel Materials* in beds and banks reflect sediment transport and hydraulic processes; they modify stream shape, pattern, and slope (Rosgen 1994). They also reflect aquatic habitat quality and bank erosion potential (Ohlander 1993). Particle size is often used to describe bed and bank materials as determined through a pebble count (Bevenger and King 1995, Wolman 1954). Channel materials are often influenced by coarser scale geologic factors as described at the valley segment level.

5. *Stream Gradient* is a refinement of segment slope criteria used at the valley segment level. It is a basic index of stream energy status. Gradient is the change in water surface elevation over at least 20 channel widths or two meander wavelengths (Rosgen 1994). Stream gradient affects aquatic habitat features (Lanka *et al.* 1987).

6. *Bed Form*, or channel bed morphology, reflects fluvial dynamics and habitat patterns governed by stream slope, sediment size and supply, and discharge; it has high covariance with other criteria mentioned above (Montgomery and Buffington 1993). Bed forms are bedrock, cascade, step-pool, plane-bed, pool-riffle, and regime (Montgomery and Buffington 1993).

7. *Riparian Vegetation* affects channel structure and stability to varying degrees. Vegetation pattern is a useful surrogate to interpret disturbance regimes and riparian-aquatic ecosystem interactions. For example, riparian peatlands can determine surface runoff, ground-water movement, and nutrient flow into associated channels (Verry and Boelter 1978). Present vegetation may not correlate with the potential natural community due to disturbances from windstorms, floods, grazing, and logging.

Stream reaches are more precise subdivisions of valley segments. Reaches have rather consistent channel forms and aquatic habitat characteristics. They provide the best resolution in the riverine hierarchy for project planning. Some reach differentiating criteria can be interpreted or measured from aerial photos and orthophoto maps (Paustian *et al.* 1984), but field sampling is usually required to accurately delineate discrete stream reaches.

Channel Units

Channel units are subdivisions of a stream reach that represent specific habitat and microhabitat units that are quite uniform in their morphologic and hydraulic properties. Channel units are areas of rather homogeneous depth and flow that are bounded by sharp gradients in depth and flow. They describe a consistent range of aquatic habitat structure and function within constraints set by valley segments and stream reaches. They constitute the most detailed level of classification for site-specific projects (Hawkins *et al.* 1993).

Uses

Variation in the structure and dynamics of channel units within a stream reach affects the production and diversity of stream biota. Different types of units are usually close enough to each other that mobile stream fauna can select the channel unit that provides the most suitable habitat. Abundance of biota and rates of ecological processes often show marked patchiness due to variations in habitat structure defined by morphology (depth, width, shape), flow hydraulics, and bed roughness or substrate size (Hawkins *et al.* 1993).

Channel units classified consistently, using criteria known to affect biota, can help determine factors that limit populations within a stream reach (Hawkins *et al.* 1993). In the Pacific Northwest, three salmonid fish species segregate within stream reaches by using different types of channel units (Bisson *et al.* 1982, 1988; Sullivan 1986). Taxonomic and functional composition of benthic invertebrates

varies among types of channel units within stream reaches (Hawkins 1984, Huryn and Wallace 1987).

This most detailed level in the riverine hierarchy is the most appropriate one to diagnose cause and effect relationships between shifts in habitat condition and changes in riparian and watershed conditions. Channel units are usually analyzed within the context of the stream reach within which they are nested.

Map Unit Delineation and Scale

Channel units are typically 10 m or less in length. They usually cannot be mapped at a scale appropriate for land management planning.

Defining Criteria

Channel units are discrete areas of rather uniform depth and flow. They are bounded by sharp physical gradients and are formed by interactions among flow, sediment load, and channel resistance to flow. Hawkins *et al.* (1993) provide a consistent hierarchical framework for classifying channel units (fig. 6).

Initially, **riffles** (fast-water habitats) are distinguished from **pools** (slow-water habitats). Riffles are high points in the bed with coarser sediments, and have rapid and shallow flow with steep water-surface slopes at base flows. Pools are low points with usually finer substrates and are deep, slow-flowing, and gently sloping. The biota in riffles and pools differ sharply in their taxonomy and their morphologic, physiological, and behavioral traits (Hawkins *et al.* 1993).

Subdivisions of pools and riffles are described using local stream bed grade, flow depth, and relationship to channel obstructions or constrictions:

a. Riffles can be subdivided into **turbulent** or **non-turbulent** classes based on differences in gradient, bed roughness, and degree of steps (breaks in slope). The types and abundances of riffle-dwelling benthos are affected by the amount of turbulence (Hawkins *et al.* 1993). These two classes of riffles can be further subdivided based on differences in such factors as:

   1. Gradient, or water-surface profile.
   2. Percent super-critical flow.
   3. Bed roughness, affected by size of substrate.
   4. Mean velocity of streamflow.
   5. Step development.

b. Pools can be subdivided into **scoured** or **dammed** classes. Dammed pools tend to collect and retain more sediment and organic debris and have more cover than do scour pools (Hawkins *et al.* 1993). These two classes of pools can be further subdivided based on differences in such factors as:

   1. Location (main channel or off-channel).
   2. Longitudinal and cross-sectional depth profiles.
   3. Substrate characteristics.
   4. Pool-forming constraint (obstructions, debris, beaver dams, etc.).

THE LACUSTRINE SYSTEM

The lacustrine system consists of lakes found in topographic depressions and reservoirs that occur in flooded river valleys. These open-water bodies nest within overlying geoclimatic and zoogeographic settings. An apparent obstacle to a hierarchical classification of lakes is their variation in size. However, variable size is not a problem if it is addressed early in the classification; the first step is to delimit a lake by the smallest geoclimatic and zoogeographic settings that encompass it. For example, at the upper size range, eight lakes in North America correspond to the province or basin scale and 49 correspond to the section or subbasin scale (Appendix B).

Setting the lower size range of lakes and differentiating them from open-water wetlands is somewhat arbitrary. Nevertheless, we define lakes as having an open water area greater than 1 ha **and** a maximum depth greater than 1 m at low water, while open-water wetlands are less than 1 ha in area **or** less than 1 m deep at low water. Recommendations for classifying wetlands appear later in this report.

Once lakes are placed into their geoclimatic and zoogeographic settings, there are three hierarchical levels within the lacustrine system: whole lakes, lake zones, and lake sites. The whole-lake properties of lakes are divided into

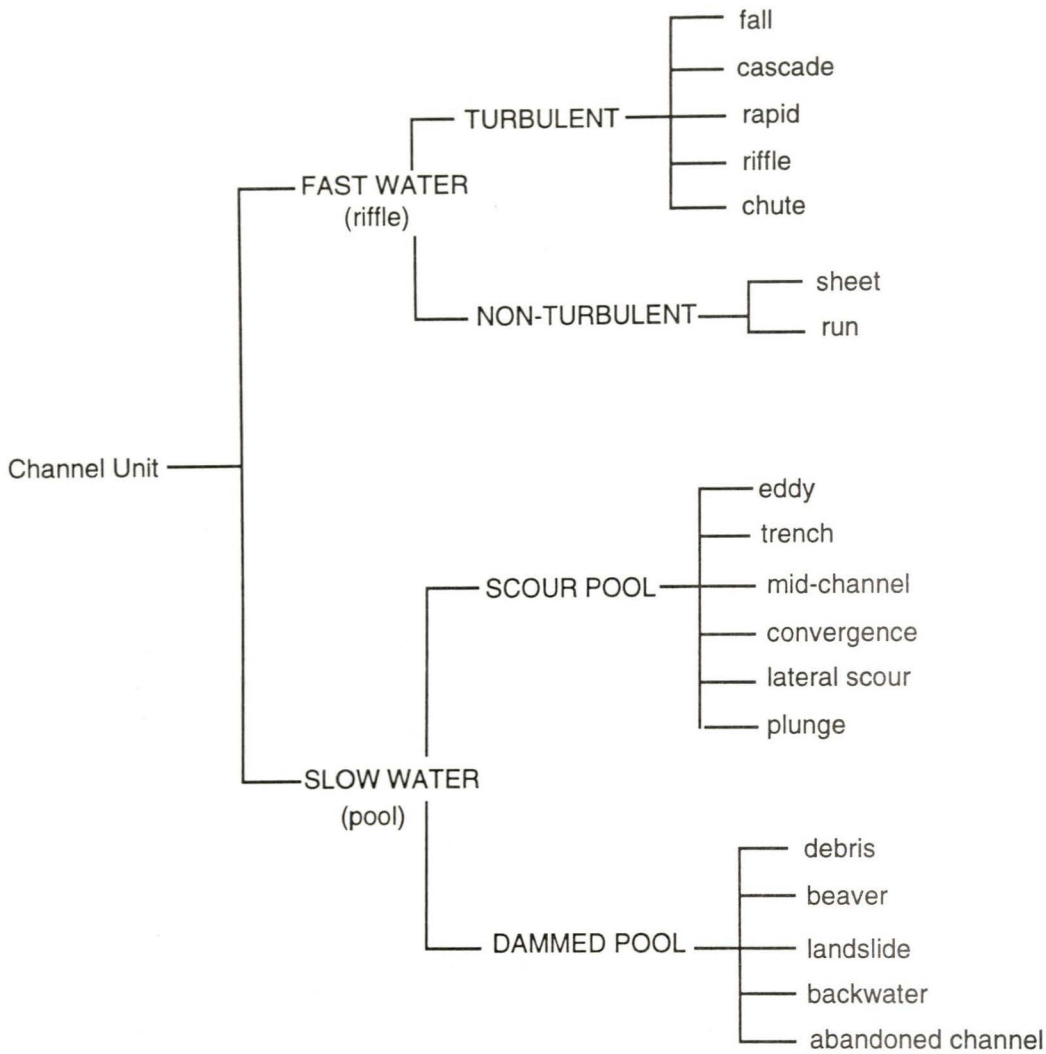


Figure 6.—*Similarity dendrogram showing how channel units can be classified with increasing levels of resolution. Three tiers of classification are shown, which can be used to distinguish classes (Hawkins* et al. *1993).*

primary and secondary attributes. The primary attributes are causative hydrogeomorphic factors used to classify lakes. The secondary attributes serve to validate the lake classes and to describe their physical, chemical, and biological properties.

Lakes

Lakes are classified by lake geology, hydrology, and morphometry. Lake geology includes lithology and geomorphology. Lake hydrology includes attributes of surface-water and groundwater connections. Lake morphometry includes area, depth, and geometry. Most of these **PRIMARY ATTRIBUTES** can be taken directly from maps and aerial photos, and they provide insight into the expected biology of the lake (Marshall and Ryan 1987). Lake classes may correlate with adjoining land units (USDA 1993). These land units should be used to help define lake classes based on their geoclimatic properties.

Uses

Distributions of aquatic biota defined by a lake's zoogeographic and geoclimatic settings are refined by geology, hydrology, and morphometry. These features determine the complexity of aquatic habitats and the historic time available for biological adaptation of the native aquatic community. They are also useful for a broad assessment of habitat quantity and quality. For example, lake depth, water linkage, and water stage determine the amount and duration of available habitat; and, along with geoclimatic setting and lake morphometry, they also affect key facets of the habitat's physical and chemical quality.

More detailed physical, chemical, and biological attributes can be predicted from information at this level, but such predictions need to be verified by data from those secondary attributes. For example, the chance that a lake will thermally stratify can be predicted from mean and maximum depth, latitude, altitude, and surface area, but can be verified only in the field.

Map Unit Delineation and Scale

Map units are determined by the size of the water body, which can range from one hectare to thousands of square kilometers. The usual mapping scale is 1:24,000 to 1:63,000, although very large lakes will require a coarser scale.

Defining Criteria

LAKE GEOLOGY includes lithologic and geomorphic features that are responsible for determining broad physical, chemical, and biological outcomes. Lake geology can be separated into two categories.

1. *Genesis*: The geomorphic process(es) that have formed a lake are deemed fundamental in classical limnology, tend to apply over large landscapes, and group lakes into categories for further analysis (Winter and Woo 1990). The 12 classes of formation process (from Hutchinson 1957) are:

   Glacial = formed by glacial scour or deposition.
   Fluviatile = formed by river activity.
   Volcanic = formed by crater collapse or lava flows.
   Tectonic = formed by land uplift or subsidence.
   Wind = formed by eolian deposits of sand or silt.
   Solution = formed by solution of carbonate rocks.
   Shoreline = formed by wave action of a larger water body.
   Landslides = formed by mass movement deposits.
   Organic = formed by buildup of peat and other deposits.
   Meteoric = formed by meteor impact creating craters.
   Beaver = formed by dams built by beavers.
   Anthropogenic = formed by dams built by humans.

2. *Physiography*: Surficial lithology and lake location (altitude, latitude, and longitude) strongly affect lake chemical and thermal regimes (Born *et al.* 1974, Winter 1977). These features can be taken directly from existing maps, and are part of each lake's geoclimatic setting. These features, either singly or together, are useful in interpreting the biological composition and productivity of lakes (Dolman 1990, Winter and Woo 1990).

LAKE HYDROLOGY includes the connection of a lake to surface or ground water and can

provide information useful in explaining inherent limnology and biology. Lake hydrology can be separated into three categories:

1. *Riverine Linkage*: The connection of a lake to a riverine system can be rated as (1) unconnected, (2) outlet only, (3) inlet only, or (4) both inlet and outlet. This information is useful to understanding lake limnology and biology. For example, a lake with no surface linkage to other water bodies is more likely to contain unique biota due to temporal isolation, as long as human-caused introductions or exploitation has been minimal.

2. *Ground-Water Linkage*: Lakes can be rated as (1) gaining (ground-water discharge prevails), (2) losing (ground-water recharge prevails), (3) neutral (recharge balances discharge), or (4) unlinked (no ground-water linkage). A sustantial ground-water linkage can modify lake level fluctuation, thermal regime, and chemical composition, thus improving or impairing habitat quality for lake biota.

3. *Water-Stage Regime*: Lakes can be rated as (1) perennial (surface water present year-round in most years) or (2) intermittent (surface water present in certain seasons). These regimes are refined by two elevation classes: constant (mean annual change of 1 m or less) and variable (mean annual change greater than 1 m). Most reservoirs and some natural lakes have highly variable surface elevations that may restrict the type of resident biota that can be sustained.

LAKE MORPHOMETRY includes physical features that, along with the other driving variables, largely determine species diversity (Eadie and Keast 1984, Marshall and Ryan 1987, Schupp 1992). All but lake depth can be derived from maps and aerial photos. The three categories of morphometric variables are:

1. *Area*: Lake area strongly affects the number of species in the context of other driving variables (Barbour and Brown 1974). Most lake classifications use surface area as a primary variable (Eadie and Keast 1984, Schupp 1992) or as part of morphometric indices to classify lakes. Lake geology and surface area are sufficient variables for a preliminary classification of lakes. For example, all lakes smaller than 10 ha within one geoclimatic area can be presumed to have similar limnology and biology. This hypothesis can be tested by using additional secondary information.

2. *Depth*: This feature is the only attribute that is rarely available from maps or aerial photos. Knowledge of maximum depth is useful, but mean depth is the preferred parameter because it contains more information about lake volume that can be linked to other attributes. Knowledge of mean depth along with the other whole-lake attributes can provide a powerful insight to the expected biology of a lake (Marshall and Ryan 1987).

3. *Geometry*: Three common indices of surface geometry are (1) orientation, or the azimuth of the longest axis; (2) shoreline development factor, or lake perimeter divided by the circumference of a circle with the same area (Eadie and Keast 1984, Schupp 1992); and (3) watershed-to-lake area ratio, which can be used with knowledge of ground-water inputs to explain lake limnology. In addition, calculation of lake volume by depth-contour methods also provides much basic information needed at the lake zone level.

SECONDARY ATTRIBUTES refine the lake classes defined by the primary attributes. Physical features focus on lake morphology, chemical features focus on water quality and nutrient status, and biological information includes attributes of the aquatic community or appropriate biological surrogate(s) characterizing a species assemblage or guild.

Secondary lake attributes provide the detail needed to evaluate physical and chemical properties of water bodies. These properties may explain the presence or absence of regional flora and fauna and infer aquatic habitat capability. Such properties include physical and chemical constituents expected given the lake's geology and morphometry. Other useful information includes gross lake productivity, which can be estimated using computed indices such as the morphoedaphic index (Ryder 1965).

1. *Temperature*: Thermal regimes are determined by lake geology, hydrology, and morphometry, and they strongly affect the biophysical classification of lakes. Aquatic organisms have adapted to long-term thermal regimes. The use of terms such as coldwater, coolwater, and warmwater species indicates the effect of lake temperature on the distribution of aquatic organisms.

2. *Stratification*: The presence or absence of a summer thermocline is a function of lake depth and geoclimatic setting. Lakes may be classified as mixed or stratified based on the presence or absence of a thermocline or in some cases a halocline. Stratified lakes differ from mixed lakes in their vertical thermal and oxygen profiles. Stratified lakes are further separated by hypolimnion oxygen content. Winter oxygen depletion, which can occur in mixed or stratified lakes, is important because it has an obvious impact on aquatic aerobes (Tonn *et al.* 1983). Mixed and stratified lakes, with or without anoxic zones, tend to have different aquatic communities (Marshall and Ryan 1987, Riley and Prepas 1985).

3. *Retention Time*: The rate of water volume flowthrough depends on lake morphometry and water budget, and indicates hydrologic variability. Retention time has been shown to be useful in assessing the trophic status of southeastern lakes and reservoirs (Reckhow 1988).

4. *Color and Clarity*: The transmission of light through water is impeded by dissolved and particulate matter in the water, which is controlled by inflow (seepage or drainage), morphometry, bottom substrate, and productivity. Light penetration and color are measured by photometry (or in most cases by a Secchi disc) or by colorimetry, respectively. Light penetration has a strong influence on planktonic productivity and patterns of aquatic macrophyte distribution (Duarte *et al.* 1986).

5. *Water Chemistry*: Alkalinity, pH, and total dissolved solids (or specific conductance) are functions of surficial geology, climate, ground water, and intralake hydrology. These chemical parameters influence aquatic habitat productivity and lake resilience to acid deposition and other introduced pollutants (Adams *et al.* 1991, Schupp 1992, Tonn *et al.* 1983).

6. *Trophic State*: Many lake classification systems are based on some measure of productivity or metabolic status. As such, lakes are typically referred to as oligotrophic, mesotrophic, or eutrophic (some limnologists view dystrophic lakes as a special case of oligotrophy). As used here, trophic state includes some measure of nutrients, typically phosphorus or nitrogen, but it does not preclude other indices that have proven useful.

7. *Aquatic Biota*: Designating the aquatic community or a surrogate of the community or guild defines the exact zoogeographic character of a lake or group of lakes.

These secondary attributes show a high degree of collinearity with the primary attributes. For example, the euphotic zone is usually manifested as the maximum depth at which rooted aquatic macrophytes can grow. This depth is a function of water clarity, longitude, and shoreline slope, which are a function of lake geology and morphometry.

These attributes and their numeric limits have regional utility for classifying lakes. Table 4 is an example classification scheme for a hypothetical set of 100 lakes in northern Wisconsin. These lakes all are of glacial origin, are less than 25 ha in area and less than 10 m deep, and have an outlet and stable water level but unknown ground-water linkage.

Trophic status and thermal regime show 20 lakes to be eutrophic-warm water. Ten of these lakes are stratified with anoxic hypolimnion and high conductivity. Seven of these ten lakes have high pH; five have no fish. A fisheries management plan in these five lakes is not indicated. However, other unique biota in these five lakes may need protection because the high conductivity and pH of these lakes suggest that they are fens, which have a strong ground-water linkage. Such conclusions can be field-verified using the parameters at the lake zone level.

Lake Zones

Lake zones are portions of a water body based mostly on depth classes. Lake zones define general habitat patterns within water bodies.

Uses

Lake zones involve physical and biochemical boundaries that, together with the properties described for whole lakes, set the form and functional limits needed to define biological characteristics of a particular lake or group of lakes. The properties described at this level refine these boundaries to the extent where specific management plans can be developed.

Map Unit Delineation and Scale

The lake zone is a subset of the water body whose size is determined mostly by the size of the whole lake. Mapping scale is usually 1:12,000 to 1:24,000.

Defining Criteria

At this level the lake is divided into zones of biological significance (Wetzel 1983). Three zones are described by depth classes:

1. *Littoral Zone* is the lake area or volume occupied by peripheral shallows in which rooted aquatic plants grow or light penetrates to some predetermined level. The littoral zone relates to primary productivity and thermal-oxygen stresses that are useful in the classification of lakes (Schupp 1992).

2. *Pelagic Zone* is the area or volume of a lake occupied by open water beyond the littoral zone. This zone represents the area where most planktonic activity occurs when it is present.

3. *Profundal Zone* is the area or volume of a lake below the pelagic zone, where light

Table 4.—*Grouping of 100 hypothetical lakes of glacial origin in northern Wisconsin that are less than 25 ha in surface area and less than 10 m deep*

Sample size=100		TROPHIC STATUS (number of lakes)		
		Oligo-	Meso-	Eu-
	Warm	0	50	20*
THERMAL REGIME	Cool	0	30	0
	Cold	0	0	0

Sample size=20*		CONDUCTIVITY		
		<40	40-100	>100
	Mixed	0	3	5
STRATIFICATION	Strat. anoxic hypo.	0	2	10*
	Strat. oxic hypo	0	0	0

Sample size=10*		FISH COMMUNITY		
		N pike/ LM bass	Mud minnow	Fishless
	<4.5	0	0	0
pH	4.6-6.8	2	1	0
	>6.8	1	1	5

penetration is too low to support primary productivity. Thus, carbon dioxide production exceeds oxygen production; in stratified lakes this feature, together with hypolimnetic volume and oxygen demand, will determine the presence or absence of anoxia.

A special case of the profundal and littoral zone is the hyporheic zone where benthic organism identity and biomass may be an important element to the classification of a lake. Aquatic macrophytes can be useful in identifying the extent of the littoral zone, and the dominant particle sizes of bottom substrate may be used to further stratify lake zones.

Lake Sites

At this level selected point features may be delimited. Such features include springs (upwellings), deltas, inlets and outlets, or similar inclusions.

Uses

Point features further refine lake form and functional properties, especially as they may be used to explain unexpected empirical results. For example, multiple inlets may explain the presence of stream spawning fish in an abundance greater than would be expected in a similar water body with only one inlet.

Map Unit Delineation and Scale

The lake site is a subset of the water body whose size is determined by the magnitude of the point feature. Mapping scale is usually less than 1:12,000.

Defining Criteria

Springs, deltas, inlets and outlets, and other detailed habitat features that may influence biophysical functions should be mapped and labeled.

THE GROUND-WATER SYSTEM

Ground water is ecologically important in two ways: (1) it can affect the hydrologic, chemical, and thermal regimes of streams, lakes, and wetlands with which it is hydraulically connected; and (2) it provides habitat for fauna in the hyporheic zone and supports many important biogeochemical interactions in ways that we are just beginning to understand.

Ground water interacts with surface water through recharge and discharge zones. Recharge occurs where precipitation or surface water infiltrates under sufficient hydraulic head to reach saturated zones. Discharge occurs as evapotranspiration or as diffuse or discrete flow into streams, lakes, or wetlands. Ground water is always moving from recharge to discharge zones as governed by hydraulic gradient, hydraulic conductivity, and porosity. Major discharge to surface water occurs from alluvial deposits into streams, from glacial deposits into lakes, and into wetlands. Aquifers may also be hydraulically connected to each other.

Ground water can move from recharge to discharge zones through regional, intermediate, or local flow systems. Over the long term, the location of each flow system is governed by climate, geology, and aquifer attributes of water storage, hydraulic conductivity, and hydraulic gradient. Over the short term, their locations and relative configurations can be affected by weather cycles, vegetation patterns, and human disturbances.

Studies on linkages between ground water and aquatic ecosystems are recent and limited (Gilbert *et al.* 1990, Winter 1992). The ground-water hierarchy presented here stresses features that most affect the scaled structure of ground-water systems and their relation to surface-water systems. This hierarchy is based on mappable features that delineate factors controlling ground-water flow systems. In order of descending scale, these units are ground-water regions, hydrogeologic settings, aquifers, aquifer zones, and aquifer sites (springs and sinks).

Ground-Water Regions

The occurrence and availability of ground water are controlled mostly by geology. Ground-water regions are geographic areas in which the composition, arrangement, and structure of rock units that affect the occurrence and availability of ground water are similar. Heath (1984) built on the work of Meinzer (1923) and Thomas (1952) to map 15 ground-water regions in the United States, which reflect the nature and extent of dominant aquifers and their relations to other units of the ground-water system (fig. 7).

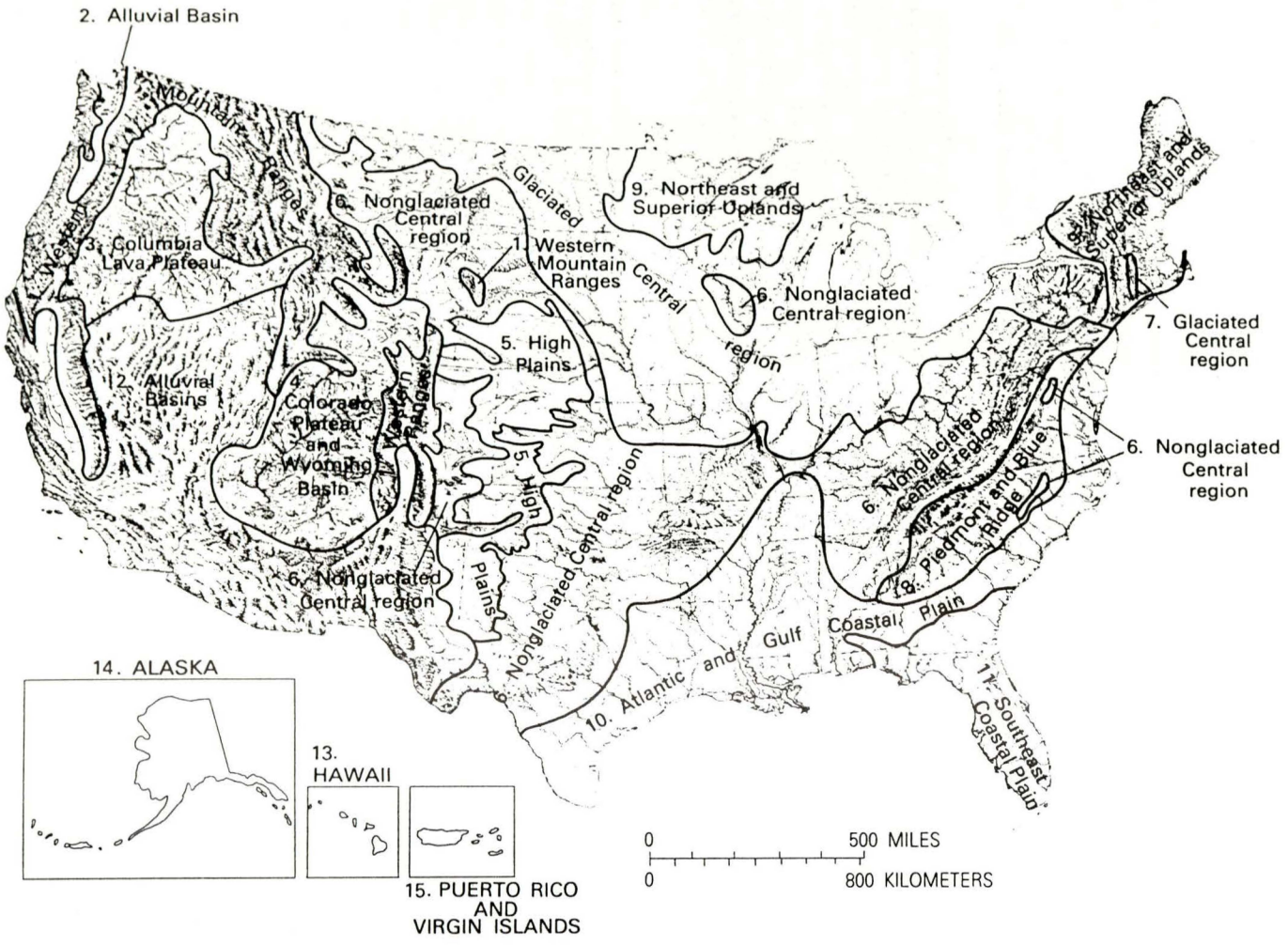


Figure 7.—*Ground-water regions of the United States (from Heath 1984). The Alluvial Valleys ground-water region is not shown.*

The subsurface features that define ground-water regions differ from the features that define river basins. Ground-water regions coincide more closely with physiographic provinces (Fenneman 1938a, 1938b). Ground-water regions can be expansive and interact with streams and lakes in many different river basins. For example, aquifers within the High Plains ground-water region underlie eight river basins along the 102nd Meridian from Nebraska to the Texas Panhandle.

Uses

Ground-water regions are useful for broad regional planning. These regions show marked differences in ground-water occurrence and availability (Heath 1984). These variations reflect potential yields to wells and springs, inherent water quality, recharge and discharge conditions, and susceptibility to pollution.

Map Unit Delineation and Scale

Map units are polygons of tens of thousands to hundreds of thousands of square kilometers, except for parts of the Alluvial Valleys region that are so narrow that they must be shown as lines at the 1:2,500,000 scale typically used at this level (fig. 7).

Defining Criteria

Five features of ground-water systems that affect the occurrence and availability of ground water are used to define ground-water regions. According to Heath (1984), these five features are:

1. The presence and arrangement of confining beds: ground-water regions may be characterized by a range of conditions from a single, unconfined aquifer to a complex, interbedded sequence of aquifers and confining beds.

2. The nature of the water-bearing openings of the dominant aquifers with respect to whether they are of primary or secondary origin: primary openings are pores in rocks and sediments; secondary openings are fractures, faults, and solution-enlarged openings in rocks.

3. The mineralogy of the rock matrix in the dominant aquifers with respect to its solubility: conditions may range from essentially insoluble, to both soluble and insoluble, to relatively soluble constituents.

4. The water storage and transport features (porosity and transmissivity) of the dominant aquifers: porosity is greatest in well-sorted, unconsolidated sediments and least in solid rock; transmissivity is greatest in cavernous limestones, lava-tube basalts, and clean gravels and least in confining beds and most solid rocks.

5. The nature and location of recharge and discharge zones in the dominant aquifers: recharge may occur via direct precipitation, losing streams, or leakage across confining beds from adjacent aquifers; discharge may occur to streams and lakes, to wetlands, or by seepage to adjacent aquifers.

The U.S. Geological Survey (USGS) has been developing a series of hydrologic atlases since 1978 (Miller 1990, Sun and Weeks 1991). These atlases contain maps and data for the ground-water regions and should be finished by 1996. Each atlas includes data needed to understand the condition and sustainability of regional ground-water resources. For example, maps show water table contours before and after major ground-water development, indicating areas where recharge-discharge gradients were altered or reversed; sites of major springs; withdrawals from each aquifer; and ground-water uses such as agriculture, mining, commercial, and domestic-public supply.

Hydrogeologic Settings

Hydrogeologic settings are subdivisions of ground-water regions (Aller *et al.* 1987). These units delineate the typical geologic and hydrologic configurations that are found in each ground-water region. Although not yet mapped for most of the United States, a suite of hydrogeologic settings have been described for each ground-water region (Appendix C). A hydrogeologic setting is an association of hydrostratigraphic units as defined by mappable physiographic features. It corresponds to, and should be used to map, subsections and landtype associations in the hierarchy of ecological land units (USDA 1993).

Uses

A hydrogeologic setting is a composite of all the major geologic and hydrologic factors affecting ground-water movement into, through, and out of an area. It is a mappable unit with common hydrostratigraphic characteristics and sensitivity to contamination by introduced pollutants. From these factors we can infer ground-water availability and pollution potential (Aller *et al.* 1987).

Map Unit Delineation and Scale

Map units are typically polygons ranging in size from tens to hundreds of square kilometers. Typical map scale is 1:250,000.

Defining Criteria

Hydrogeologic settings are defined by the hydrologic character of geologic units within ground-water regions (Appendix C). Descriptive details for mapping these units appear in Aller *et al.* (1987). Similar criteria are used to map subsections and landtype associations in the land system hierarchy (USDA 1993).

Aquifers

An aquifer is a water-bearing geologic formation, group of formations, or part of a formation that contains sufficient saturated permeable material to yield water in a usable quantity to a well or spring (Heath 1984, Lohman *et al.* 1972). Within each aquifer, ground water moves from areas of recharge to areas of discharge. Flow direction, velocity, and discharge rates are controlled by aquifer porosity, hydraulic conductivity, and hydraulic gradient.

Uses

Mapping of aquifers identifies the areal extent and location of the ground-water resource. Relative potential for ground-water development and pollution can be inferred, and ground-water development and protection plans can be developed. Such information is useful for regional and local planning.

Aquifer classification describes the overall physical and chemical state of the aquifer, reflects the yield and quality of its ground water, and implies the ease with which it may be developed or impacted. Potential for interaction with surface water systems and land management activities can be inferred.

Map Unit Delineation and Scale

Map units may range from a few to hundreds of square kilometers. The recommended mapping scale is 1:24,000 to 1:63,000.

Defining Criteria

Aquifers are described by their geology, hydrology, and water quality. Geology is used to classify and map aquifers. Hydrology and water quality are descriptive attributes. An aquifer's **geology** includes the consolidation, confinement, and composition of aquifer strata:

1. Aquifer consolidation is the degree of cementation of geologic materials (AGI 1972). Consolidated aquifers consist of rock, and unconsolidated aquifers consist of loose sediments.

2. Aquifer confinement reflects the ground-water pressure (Heath 1984, Lohman *et al.* 1972). Confined aquifers are fully saturated under pressure greater than atmospheric, bounded above and below by geologic units that have much lower hydraulic conductivity. Unconfined aquifers have a saturated and an unsaturated zone, separated by a water table that is at atmospheric pressure.

3. Aquifer composition is the lithology, structure, and thickness of the water-bearing materials. Lithology and structure determine porosity and permeability, which, with the saturated thickness, determine the aquifer's capacity to yield water.

Aquifer **hydrology** includes hydraulic conductivity, transmissivity, recharge and discharge rates, storage, and hydraulic head and gradient. The factors shown below determine water-bearing and transmission characteristics (Heath 1984):

1. Hydraulic conductivity is the volume of water transmitted by the aquifer in unit time through a unit area under a unit hydraulic gradient. Transmissivity is the

aquifer's capacity to transmit water and is equal to the hydraulic conductivity multiplied by the saturated thickness.

2. Recharge and discharge rates are the amounts of water received by and lost from the aquifer per unit area per unit time. Storage is the amount of water contained in the aquifer and is related to porosity.

3. Hydraulic head is the elevation of the column of water that can be supported by the hydraulic pressure at a given point. Hydraulic gradient is the slope of this hydraulic head.

Aquifer **water quality** is a function of the dissolved chemical and biochemical constituents and the chemical and microbiological processes in operation. These factors affect the ground water's ability to support various biotic processes and human uses. Water quality parameters include cations, anions, pH, temperature, alkalinity, salinity, metals, radionuclides, and biological constituents.

Aquifer Zones

Aquifer zones are subdivisions of aquifers with differing hydrologic conditions. Aquifer zones include recharge and discharge areas as well as confined and unconfined areas. Locally important links to surface-water systems that may be obscured at coarser hierarchical levels are identified at this level. Recharge may occur through direct precipitation, losing streams and lakes, or leakage from other aquifers. Discharge may occur to gaining streams, lakes, and wetlands, by evapotranspiration, or by seepage into adjacent aquifers.

Recharge zones are usually greater in area than discharge zones. Regionally significant recharge and discharge zones can occur in discrete localized areas (recharge through fault zones or sinkholes, discharge through springs, etc.). Any one stream, lake, or wetland may have both gaining and losing portions, but in certain hydrogeologic settings, either recharge or discharge may predominate.

Uses

Aquifer zones are ecologically important in identifying ground-water interactions with surface-water systems and wetlands. Ground-water discharge into streams and lakes typically moderates their water level fluctuations and thermal and chemical regimes. Habitat quality for aquatic biota may be improved or impaired. Ground-water discharge zones often coincide with large wetlands whose productivity and diversity depend on the abundant water constantly supplied by the aquifer.

Aquifer discharge can increase fish production. For example, warm ground-water inflow to the Chilkat River in Alaska provides ice-free winter spawning habitat for late run chum and silver salmon (Bugliosi 1988). In addition, aquifer-fed channels on two rivers in the Olympic Mountains of Washington have only 3 to 6 percent of the summer rearing habitat for coho salmon, but provide 29 to 36 percent of their juvenile production (Sedell *et al.* 1983).

Map Unit Delineation and Scale

Aquifer zones are polygons or lines that are appropriately mapped at the 1:12,000 to 1:24,000 scales.

Defining Criteria

Aquifer recharge and discharge zones can often be inferred from map and photo interpretation. These zones can be inferred from aquifer outcrops, breaks in land slope such as hingelines, and hydrograph signatures that may indicate the occurrence of recharge or discharge. Wetlands are often important aquifer discharge zones.

Recharge and discharge zones connected with surface-water systems must usually be identified in the field. Flow and water level measurements and water tracing are usually used to identify ground-water flow into and out of streams and lakes.

Aquifer Sites (Springs and Sinks)

As noted in the previous section, entire stream reaches and lakes can discharge into, or receive recharge from, aquifer zones. Recharge and discharge can also occur at specific features such as sinks and springs. Sinks and springs may be single points, clusters of points, or linear features along streams. Underground rivers in karst terrane are usually connected with surface-water systems through springs and sinks.

Uses

Springs, sinks, and underground rivers identify potential sources of ground-water development and pollution and major linkages between surface and ground water and their biota. Mapping these features permits these major linkages to be evaluated and enhances protection of water quality and aquatic biota in both systems.

Map Unit Delineation and Scale

Springs, sinks, and underground rivers are commonly mapped at the 1:12,000 to 1:24,000 scale.

Defining Criteria

Springs may be classified by their discharge, type of discharge opening, aquifer type, and water quality. The most commonly used classification criteria are mean discharge (Meinzer 1923) and hydrogeologic features (Baker and Foulk 1975). The eight magnitudes of mean discharge (liters per minute) are:

1st = 170,000 +	5th = 38 to 380
2nd = 17,000 to 170,000	6th = 3.8 to 38
3rd = 1,700 to 17,000	7th = 0.5 to 3.8
4th = 380 to 1,700	8th = Less than 0.5

Hydrogeologic features (Baker and Foulk 1975) chiefly reflect the relationship between the spring, geology, and topography. The eight major types are:

1. Artesian = release of pressurized water from a confined aquifer at the aquifer outcrop or through an opening in the confining unit.

2. Contact = water flows from a permeable water-bearing unit that overlies a less permeable unit that intersects the ground surface.

3. Depression = water flows from a ground-water depression that intersects the water table.

4. Fracture = ground water moves predominantly through fractures and emerges where the fractures intercept the ground surface.

5. Geyser = periodic thermal spring resulting from expansive force of super-heated steam within constricted subsurface channels (Todd 1980).

6. Perched = infiltrating water discharges above the regional water table from a permeable geologic unit that overlies a less permeable unit.

7. Seep = water discharges from numerous small openings in permeable earth material, usually at very low discharge rates.

8. Tubular = water discharges from rounded channels such as karst solution openings and lava tubes.

Sinks are chiefly formed by solution of bedrock or semi-consolidated sediments. They can be classified by mode of ground-water recharge (Palmer 1984), which is strongly related to subsurface solution features and surface karst features. The three major recharge modes are: (1) *diffuse* through permeable material producing network cave patterns; (2) *authigenic* through many discrete sources such as sink holes, producing dendritic cave patterns; and (3) *allogenic* through a few major inflow points such as sinking streams, producing braided cave patterns. These recharge-solution patterns have different surface-water/ground-water interactions.

HYDROGEOMORPHIC CRITERIA FOR CLASSIFYING WETLANDS

Wetlands are fundamentally hydrologic features that exist where physiography and water balance favor the retention of water (Winter 1992). Wetlands occur in low areas where water accumulates, along rivers or lakes where flooding occurs, or on slopes and uplands because of ground-water discharge, breaks in slope, geologic contacts, or slow subsurface drainage (Winter 1988). By our definition, open-water wetlands are less than 1 ha in area **or** less than 1 m deep, which distinguishes them from the lacustrine system.

According to Winter and Woo (1990), the formation of wetlands in any area is governed by landform, geology, and hydrology. Landforms favoring wetlands include depressions into

which surface and subsurface water drains, areas of low relative slope that retard runoff, and breaks in slope that intersect the water table. Geologic factors that favor wetlands include impermeable organic and inorganic soils, changes in aquifer geometry, and permafrost. Hydrology, which is governed by climate (precipitation minus evapotranspiration) and surface and subsurface flow systems, must furnish an adequate and persistent water supply.

The physical, chemical, and biological processes of a wetland are tightly interwoven. A framework is needed that identifies common factors fundamental to all wetlands, especially those geomorphic, climatic, and hydrologic controls that govern many wetland functions. Such a framework will allow wetlands in any area to be placed in a hydrogeomorphic context that strongly affects their flora and fauna (Brinson 1993, Winter 1992).

A classification that first establishes this hydrogeomorphic context (Brinson 1993, Winter 1992) and then introduces soil and vegetation factors (Cowardin *et al.* 1992) will maximize our understanding of wetland forms and functions. We **strongly recommend** that the ECOMAP effort adopt this approach as outlined below and consult other references such as Gore (1982) and Verry (pers. comm.).[1]

Fundamental Hydrogeomorphic Criteria

The basic hydrogeomorphic criteria for classifying wetlands (Brinson 1993, Winter 1992) occur in four groups (physiography, climate, water source, hydrodynamics) that emphasize the ecological function of wetlands. Physiographic classes are shoreline, riverine, depressional, peat, and permafrost. Climate refers to precipitation and temperature regimes. Water sources are precipitation, ground-water discharge, and lateral inflow. Hydrodynamics classes are vertical fluctuations, unidirectional flow, and bidirectional flow.

A. Physiography

Physiography is the location of the wetland in the general landscape (Winter 1992) and reflects drainage systems and patterns that influence the flow and storage of water (Brinson 1993). Five major geomorphic types are recognized, all of which have subtypes:

1. ***Shoreline wetlands*** occur along ocean coasts where tides dominate or along large lakes where waves and seiches move water in and out. Complex flow paths and chemical exchanges result from the interaction of such forces with local ground-water flow systems that affect the wetland. Bidirectional flow dominates and the hydroperiod is long. These wetlands are among the most productive and important ecosystems on Earth.

   a. Coastal wetlands are typically located in estuarine settings, are subjected to astronomic tides, and are often sea-level controlled. They form barriers to sea water encroachment, increase sediment deposition, and are open to estuarine fauna for feeding and recruitment.

   b. Lakeshore wetlands are located in lacustrine settings, are subjected to seiches, and are lake-level controlled. The lake supplies water to the wetland and establishes hydroperiod gradients for wetland zonation. These wetlands stabilize lake shorelines and provide transition habitat used by both aquatic and terrestrial biota.

2. ***Riverine wetlands*** form linear strips on river flood plains and terraces. They are affected by river flows and have mostly unidirectional flow, but are also major regional ground-water discharge areas. Regional ground-water flow systems dominate near valley walls, local ground-water flow systems dominate on lower terraces, and river flooding dominates on flood plains. Hydroperiod is short and flashy in headwater streams to long and steady in large rivers.

   a. Intermittent stream wetlands occur along headwater streams in which flow is seasonal and overbank flooding has little effect. Ground-water and surface-water sources change

[1] *As stated in Minnesota DNR memo "Technical criteria for identifying and delineating calcareous fens in Minnesota" dated August 2, 1994, 22 p.*

phases, and the riparian wetland is vital as a buffer to maintain stream water quality.

b. Steep riverine wetlands occur in local deposition areas along mostly erosional stream segments. Flow velocity and hydraulic conductivity are high, and wetland sediments are coarse gravels and cobbles. Large woody debris may control channel and wetland structure, and riparian vegetation contributes to allochthonous organic supply.

c. Moderate riverine wetlands occur along mostly transport stream segments where erosion and deposition are balanced. Channel processes produce varied hydroperiods and habitats. Wetland sediments are fine gravels and coarse sands. Large woody debris and allochthonous organic supply often strongly affect wetland structure and function.

d. Gentle riverine wetlands occur along mostly deposition stream segments. Floods and deposition dominate formation of wetlands, which store flood waters, discharged ground waters, and nutrients. Wetland sediments are fine sands, silts, and clays. Habitats are extensive and diverse. Beaver activity often creates wetlands in these settings.

e. Flat riverine wetlands occur along drainages where surface flow is strong enough to be recognized, but not strong enough to create more than shallow channels. Fluvial processes are weak, channel roughness is high, and vegetation modifies the substrate by depositing organic sediments.

3. ***Depressional wetlands*** occur in topographic depressions. Where they occur high in watersheds, they typically depend on atmospheric exchanges more than other wetlands. In dry climates, these wetlands either are dry much of the time or depend on ground-water sources. In humid climates, they may develop enough peat to develop a domed relief and depend on precipitation inputs.

a. Playa wetlands occur in arid lowlands and are dominated by surface inflow and evaporation. Their ground-water flow systems, geochemical processes, and biota often differ from those of other wetlands.

b. Morainal wetlands are found in undrained or poorly drained glacial moraine depressions. Surface- and ground-water hydrology is typically complex. Stream networks tend to be poorly integrated. A morainal wetland can be a site of ground-water recharge, discharge, or both. Ground-water flow reversals at edges are common.

c. Dune field wetlands occur in interdunal lowlands. Infiltration is high, and stream networks are poorly integrated. Ground-water hydrology is often complex, and ground-water flow reversals at edges are common.

d. Karst wetlands are formed by solution of carbonate rocks. Relative effects of local and regional ground-water flow systems are complicated by the geology at depth, whose resulting flow fields can dominate the wetland hydrology.

e. Slope break wetlands occur at local breaks in land slope. They are formed by a seepage face where ground-water flow intersects the surface, or by base seepage where the upward movement of ground water occurs into the bottom of the wetland. Ground-water inflow is steady, and oxidized conditions due to frequent water movement are common.

f. Pocosins have a domed relief on a local topographic high and have surface outlets only. The water table may be significantly below the wetland much of the time. The surface outlet controls the maximum depth of the wetland.

g. Coastal plain bays have an elliptical shape, northeast-southwest orientation, no outlet, and unique biological features.

4. ***Peat wetlands*** cover large areas so that the peat substrate dominates water movement and storage, plant mineral nutrition, and landform patterns. Expansion of tertiary mire develops surface patterns independent of the underlying topography. A gradient tends to occur from the truly headwater ombrotrophic bogs to downstream fens with inlets and outlets.

    a. Ombrotrophic bogs have a peat substrate and can ultimately develop a domed relief. Precipitation dominates water inputs, saturation is often continuous, and pH and nutrients are low. Species composition is unique to bog conditions.

    b. Fens also have a peat substrate and are saturated most of the time. Ground-water supply is significant, pH is more neutral, and nutrients are higher than in bogs.

5. ***Permafrost wetlands*** are underlain by permafrost that is commonly 1 m or less below the surface. Spring snowmelt yields large surface flows because the permafrost inhibits infiltration. The only water available for evapotranspiration during the short growing season is above the permafrost.

    a. Arctic wetlands are underlain by continuous permafrost, which prevents interaction of the shallow thawed layer with regional ground-water systems.

    b. Subarctic wetlands are underlain by discontinuous permafrost, which allows shallow ground water to interact with deeper ground water.

B. Climate

Winter (1992) identified climate as a driving variable for the classification of wetlands. Precipitation and temperature regimes profoundly affect water budgets and rates of physical, chemical, and biological processes in wetlands.

Winter (1992) broadly classified precipitation regimes as wet-dry and thermal regimes as warm-cold. Another approach is to use quantitative precipitation and temperature regimes. Thornthwaite (1948) defined nine climatic types based on a moisture index of mean monthly relationships between precipitation and potential evapotranspiration. The nine types are arid, semiarid, subhumid (dry and wet), humid (four classes), and perhumid.

The Soil Conservation Service (SCS 1975) identifies six soil temperature regimes in North America based on mean annual soil temperatures and differences between summer and winter soil temperatures. The six soil temperature regimes are pergelic, cryic, frigid, mesic, thermic, and hyperthermic.

We recommend that the climatic type of each wetland be classified by these precipitation and temperature regimes. Because climate is a key driving variable in the classification of land systems (USDA 1993), these wetland climatic types nest well within mapped subsections, landtype associations, and landtypes.

C. Water Source

The dominant source of water supply affects the geochemical character of a wetland. For example, ground water discharged into a wetland has been in contact with the mineral content of the aquifer or soil. Depending on the duration of contact and the composition of the lithology, such water normally has much higher nutrient content than water derived from direct precipitation. Therefore, plant communities in wetlands that receive ground-water discharge tend to be more productive than those in ombrotrophic bogs (Brinson 1993).

Principal water sources are: (1) precipitation; (2) ground-water discharge (usually into and through wetland sediments); and (3) surface or near-surface inflow from tides, stream flooding, or overland flow or subsurface interflow (Brinson 1993). The dominant water source, which is most prevalent among the three, is designated by Brinson (1993) as follows:

1. *Precipitation*: Precipitation dominates wetland water balance and exceeds potential evapotranspiration during growing seasons. Rarity of water table drawdown promotes organic matter accumulation and retards drainage. Plants become isolated from mineral soil, resulting in low primary production.

2. *Ground-Water Discharge*: Water supply occurs through seeps or ground-water upwelling. Ground water supplies nutrients, renews water, and flushes potential plant growth inhibitors, creating conditions conducive to stable plant communities of high productivity.

3. *Lateral Inflow*: Overbank or soil water inflow during runoff events contributes to flashy hydroperiod and vertical accretion of sediments, which supplies nutrients and promotes rapid biogeochemical cycling. Conditions are maintained for high primary productivity and complex habitat structure.

D. Hydrodynamics

Hydrodynamics refers to the dominant motion of water and its capacity to transport sediments, flush saline water from sediments, and transport nutrients to root systems (Brinson 1993). Hydrodynamics is inferred from flow velocity, rate of water table fluctuations, sediment sizes, and replenishment of soil moisture depleted by evapotranspiration. Three major types of hydrodynamics are vertical fluctuations, unidirectional flow, and bidirectional flow, which correspond to depressional, riverine, and shoreline wetlands, respectively.

1. Vertical fluctuations of the water table result from evapotranspiration and subsequent replacement by precipitation and ground-water discharge. Two key variables affecting vertical fluctuation are evapotranspiration rate and replacement frequency.

   a. Seasonal fluctuations nested within multiyear cycles are common in prairie potholes. Flood water is retained by depressions, and the ponds vary in depth at any time. Water retention creates wet/moist habitats, which are vital flyway and breeding sites for waterfowl.

   b. Wide water-table fluctuations typified by evapotranspiration-caused drawdowns interspersed with frequent rain-caused saturation are common in warm, humid climates. The fluctuating water table is conducive to rapid biogeochemical cycling. Atmospheric exchanges are strong.

   c. Prolonged growing-season drawdowns broken by brief flooding periods are common in arid climates or where recharge sources are minimal. The frequent water deficits promote intermittent wetlands such as vernal pools, which often support rare floral and faunal communities.

   d. Alternating recharge and discharge are common in shoreline and riverine wetlands subject to changes in water stage. Exchange between surface water and ground water is high, which often results in well-aerated and flushed substrates that support hydrophytic vegetation.

   e. Shallow, stable water tables are common in cool, humid climates or where ground-water discharge is strong. The stable water table promotes peat accumulation, producing ombrotrophic bogs where evapotranspiration is low and fens or seepage slopes where ground-water recharge is strong.

2. Unidirectional flow can range from extremely slow surface and subsurface movement to strong currents. Surface transport of water and sediment is common. Interacting changes in water flow and slope gradient create rather sharp differences in ecosystem functions.

   a. High flow velocities are associated with steep landforms and coarse sediments. Strong currents ensure active geomorphic processes, and the wetland is well aerated and flushed because of high water turnover rates.

   b. Moderate flow velocities correlate with intermediate landforms and sediment sizes. Well-flushed and stagnant areas are often interspersed, which supports complex food webs and the import and export of nutrients.

   c. Low flow velocities correspond with gentle landforms and fine sediments. Long residence times create a low-energy system that traps sediment and nutrients and supports strong food webs.

3. Bidirectional flow can be generated by astronomic tides along ocean coasts or winds along large lakes. The cumulative effects of recurrent tides and seiches become a dominant force in the function of these ecosystems.

   a. Astronomic tides produce regular flooding of coastal wetlands once or twice daily, except in landward zones where flooding is irregular during extreme tides and storms. Regular flooding creates active biogeochemical processes and food webs, while irregular flooding creates ecotones.

   b. Lake seiches directly affect lake-level wetlands and indirectly affect more elevated wetlands by modifying ground-water levels. Shallow water and vegetation promote habitat complexity and food production.

Modifiers

Water and substrate characteristics can aid in wetland classification because they are a product of ecosystem processes and functions. Such characteristics roughly correspond with physiography, climate, water source, and hydrodynamics, so they tend to add dimensions to classification instead of proliferating the number of wetland types. Modifiers include salinity, chemistry, water color, nutrient status, and soil (Brinson 1993).

Salinity controls the composition of flora and fauna in wetlands. Fresh (less than 0.5 ppt) and oligosaline (0.5-5.0 ppt) systems are dominated by terrestrial water sources. Mesosaline (5-18 ppt) and polysaline (18-30 ppt) systems favor salt marsh and mangrove communities. Eusaline systems (30-40 ppt) are dominated by marine water sources, and nutrients likely limit plant growth. Hypersaline systems (more than 40 ppt) are common in arid climates, and salinity stresses limit wetland processes (Brinson 1993, Cowardin *et al.* 1992).

Chemistry affects plant composition. Acid systems (pH less than 5.5) reflect either low ion content with weak buffering capacity or substantial organic acids, favor peat accumulation, and restrict denitrification. Circumneutral systems (pH 5.5 to 7.4) reflect some ground-water contact with mineral substrate. Alkaline systems (pH more than 7.4) reflect heavy ground-water contact with carbonate or sulfate substrates (Brinson 1993, Cowardin *et al.* 1992).

Water color reflects history of ground-water contact with the substrate. Clear water indicates ground-water contact chiefly with soils finer than sands. Black water stained by humic and fulvic compounds indicates ground-water contact with organic sediments or sandy soils (Brinson 1993).

Nutrient status may imply rates of primary production and food web support. Oligotrophic systems indicate lack of contact with mineral soil and may suffer changes in plant composition if rate of nutrient intake is increased. Eutrophic systems often have high primary and secondary plant production. Mesotrophic systems are not distinctive (Brinson 1993).

Soils are mineral (sand-silt-clay composition) or organic (high percent loss on ignition). Mineral soils undergo thorough flushing and growing-season drawdown of the water table, which permits soil organic matter to decompose. Organic soils have long hydroperiods and low decomposition rates (Brinson 1993, Cowardin *et al.* 1992).

USES OF THE AQUATIC FRAMEWORK

Ecological classifications may be used to map ecological potential, conduct ecological analyses, identify desired conditions, monitor the effects of management, and evaluate current and emerging issues (USDA 1993). This framework for aquatic systems may be used for these applications at temporal and spatial scales similar to those described for terrestrial units (USDA 1993). Users will be able to:

1. Identify aquatic ecological unit boundaries that encompass planning units, which may be as large as a State or as small as a watershed for a spring.

2. Describe the ecological potential and natural disturbance regimes of the ecological unit being evaluated.

3. Compare existing conditions with potential conditions given the needs of people and the mix of potential management prescriptions.

4. Work with others on specific information needs within the context of a uniform and consistent data structure.

This hierarchical framework is essential to ecological analysis, planning, and monitoring of aquatic systems. Its strength is its ability to infer hydrologic and biotic processes from patterns of mappable landscapes, hydrologic units, and aquatic systems. These units have distinct forms and functions that allow the vast variation in natural systems to be systematically categorized. Scientists and managers can extrapolate knowledge from studied to unstudied areas and can integrate data from diverse sources at various levels of resolution (Conquest *et al.* 1993). Specific examples of user applications are discussed below.

Biodiversity Conservation

Physiography is a key element in defining ecological land systems (USDA 1993). Hydrography is used to define hydrologic units with zoogeographic significance from subzones to river basins. Subbasins are physiographic subdivisions of river basins. Because these subbasins combine physiographic and hydrographic criteria, they define and explain very distinct distributions of species and genetic stocks of native fish. Genetic stocks of fish may be further stratified within subbasins along watershed and subwatershed boundaries.

Assessment of aquatic biodiversity evaluates changes in these biotic patterns caused by fishing pressures, introduction of exotic species and stocks, hydrologic modifications such as dams and diversions, and habitat impacts such as sediment and toxic mine drainage. Even if habitat conditions are robust, fish distributions and numbers may have been altered by other factors; therefore, all potential factors must be evaluated.

Once we know the original biotic patterns and deviations from them, we can develop conservation plans that progress toward desired population distributions and numbers. The protection of endangered, threatened, and sensitive species can be matched to the original ranges and habitat patterns of those species. The reintroduction of native species can come from stocks that are genetically identical or as close as possible to the original populations.

Watershed Analysis

Ecological land units accommodate ecosystem management for terrestrial flora and fauna (USDA 1993). These units that can be identified at multiple hierarchical scales based on climate, geology, and landform. These three factors define the moisture, temperature, and nutrient regimes that control the patterns of vegetation and terrestrial habitats an area can produce.

Hydrologic units are also vital for ecosystem management for soil, water, and riparian systems (Lotspeich 1980, Odum 1971). Each hydrologic unit integrates inputs of water and energy with its geology, landforms, soils, and vegetation to produce a range of aquatic patterns and processes and to deliver all outputs of water, sediment, and chemicals to the main streams. What happens on the land affects the water and its dependent biota and uses.

Hydrologic units are also important because they define connected stream networks that have important biophysical and biodiversity implications. Stream networks expand and contract in response to runoff events, transporting sediment and chemicals from the headwaters and making critical habitats temporarily available to aquatic biota (Hewlett 1982). The stream network defines a continuum in which physical, chemical, and biological processes are linked from headwaters to outlet and with adjacent riparian ecosystems (Hynes 1970, Vannote *et al.* 1980).

Omernik (1987) mapped ecoregions to distinguish areas of differing water quality potential. Aquatic communities have also been correlated with ecoregions (Hughes *et al.* 1993). Our framework recognizes the importance of ecoregion (geoclimatic) settings to fish distributions within subbasins, and the linkages among patterns of ecological land and aquatic units. However, ecoregions alone do not explain all patterns of aquatic biota or account for all boundaries that constrain flows of energy and material. Ecoregions and hydrologic units are both needed to define aquatic patterns and analyze watershed processes (Hughes *et al.* 1993).

Watershed analysis includes the diagnosis of the health of a watershed in terms of its ability to maintain ecological processes and functions. Analyses benefit from consistent measures of

ecological condition. This consistency is not possible without a standard framework of ecological land and aquatic units.

In each landscape, a balanced range of dynamic equilibrium conditions exists for its watersheds and for each land and aquatic type. These ranges can be defined by sampling reference (least-disturbed) watersheds and reference members of the land or aquatic types in that landscape. These ranges of reference conditions can be used in watershed analysis to compare each watershed and each land and aquatic type against their own capabilities. Our aquatic framework provides a template of aquatic units that enables such comparisons to be consistently made for aquatic systems.

Management Prescriptions

Aquatic ecological units such as valley segments and lakes are defined by ecological factors that reflect different ecological capabilities and responses. For example, a steep, incised valley will differ from a flat, broad valley in its capability to produce aquatic and riparian biota and in its fluvial response to changes in flood flows, sediment loads, and bank stresses. Similarly, a cold, deep, and alkaline lake will differ from a warm, shallow, and soft-water lake in its biotic capability and resilience to pollution. These differences are critical to management of streams and lakes and their adjoining lands.

Management prescriptions have historically been developed for large land areas. With the delineation of geoclimatic subsections and landtype associations, such broad management prescriptions can be designated to better fit the ecological capabilities and responses of the land. Delineation of valley segments and lakes that differ in their ecological capabilities and responses should promote more rigorous management prescriptions for streams, lakes, and riparian areas within the broader landscape settings. These management prescriptions will strengthen project design and anlaysis at finer scales.

Inventory and Monitoring

Effective inventory and monitoring must focus on critical diagnostic attributes that can be compared spatially and temporally. Sampling designs can be developed once these attributes are defined. The aquatic framework supports cost-effective, stratified sampling schemes. Stratified schemes assume that discrete units can be defined at any given scale, and are designed to test the hypothesis that units with similar attributes behave similarly. Such units can be sampled and extrapolated to similar unstudied units.

A suite of attributes is measured in sampled aquatic units. These values can be compared to the same values for reference (least-disturbed) units of that type to compare existing with potential condition. Continued sampling over time gives an indication of trend. This approach provides a foundation for program and project monitoring at any desired scale.

A Final Observation

Some users expect that one universal classification exists for streams. A useful stream classification must encompass broad temporal and spatial scales, integrate structural and functional attributes under various disturbance regimes, convey information about cause and effect, be low in cost, and promote good and consistent understanding among resource managers (Naiman *et al.* 1992).

Our aquatic framework places the classification criteria identified by Naiman *et al.* (1992) and the stream classifications described by many authors such as Cupp (1989), Frissell *et al.* (1986), Montgomery and Buffington (1993), Parrott *et al.* (1989), Paustian *et al.* (1992), and Rosgen (1994) into an ecological context for North America that includes lakes and ground water. The key principles of ecosystem management are not universally satisfied by any one existing method.

Classification must be coordinated to ensure map unit integrity and corporate data continuity at ecological scales that span administrative boundaries. It is critical that aquatic ecological classification and inventory applications be blended with guides of the Federal Geographic Data Committee, the U.S. Environmental Protection Agency, and the U.S. Geological Survey, as well as classification and data standards for water used by States and tribal governments.

APPENDIX A

WATERSHED AND STREAM NETWORK DELINEATION

Delineation of watershed boundaries and the total stream network allows watershed morphology to be described and the stream network to be stratified. Streamflow and sediment processes and aquatic habitat relationships can then be interpreted.

Delineation of Watershed Boundaries

The Hydrologic Unit Code system (Seaber *et al.* 1987) is a standard watershed map system used by state and federal agencies. The first four hierarchical levels are mapped nationwide by the U.S. Geological Survey (USGS). This section shows how to map 5th-level and smaller watersheds, which are not mapped by the USGS.

Watershed level differs from watershed order. Watershed level reflects relative watershed area, and larger numbers indicate smaller watersheds. For example, a 5th-level watershed contains 6th-level subwatersheds and is part of a 4th-level subbasin. Watershed order reflects stream network structure, and larger numbers indicate larger watersheds. For example, a 4th-order watershed contains all the area draining to the mouth of a 4th-order stream (Strahler 1957).

The following rules are designed to ensure accurate and consistent delineation of watershed boundaries. These rules are written so that watershed boundaries can be input to a Geographic Information System.

Materials

Before mapping, become familiar with the local terrain to promote accuracy in delineating watershed boundaries. You will need the following materials:

1. USGS 4th-level watershed maps (1:500,000 scale) for the State and the list of codes for 4th-level watersheds (cataloging units).
2. USGS 1:100,000-scale topographic maps covering all 4th-level watersheds to be subdivided (USGS 1:250,000-scale topographic maps are optional).
3. The 1:126,720-scale Forest Recreation Map, updated to reflect current boundaries of National Forests and Grasslands.
4. Primary Base Series (PBS) maps (or 1:24,000-scale topographic maps if more current), with the total stream network shown on the maps or overlays.
5. Aerial photos at 1:24,000 or finer scale to help interpret indistinct drainage divides.
6. Blank matte mylars pin-registered to the PBS or topographic map.
7. Pen with line width of about 0.6 mm.
8. Rub-on crosses and labels.

Mapping Process

To delineate watershed boundaries, you must have good map reading skills and be able to interpret drainage divide and stream patterns from contours. Follow these guidelines when mapping watersheds at any level:

1. Use contour and drainage patterns to accurately interpret and locate watershed boundaries. Start from the outlet and follow drainage divides by bisecting ridges, saddles, and contour lines of equal elevation, until you close the watershed boundary. In flat terrain, refer to roads, trails, and firebreaks, which often follow drainage divides. Watersheds usually extend beyond National Forest and State boundaries.
2. Ignore water diversions and stock ponds when delineating watershed boundaries. However, use a water facility (dam, diversion, stream gauge), a stream confluence, or a geomorphic break to divide a watershed into upper and lower parts. Close the mouths of tributary watersheds where their main stem enters a lake, and show the remaining areas draining into the lake as one or more **COMPOSITE** watersheds (see next page).

3. Adjust watershed boundaries to conform to municipal and drinking supply watersheds where practical. Municipal watersheds serve 25 or more people or 15 or more connections (Safe Drinking Water Act, PL 93-523; FSM 2542.05).

Use the following steps to map 5th-level and smaller watersheds:

1. It often helps to delineate 5th-level watersheds on the 1:250,000-scale topographic maps to identify the extent of watershed areas outside the Forest and obtain the proper 1:100,000-scale and 1:24,000-scale topographic maps.

2. Highlight all streams already shown on the 1:100,000-scale topographic map with a blue fine-tip felt marker, so you can see the drainage network more easily over other map features. Also highlight the Forest boundary (from the 1:126,720-scale Forest map) on this 1:100,000-scale map.

3. Transfer all existing 4th-level watershed boundaries to the 1:100,000 scale map using a heavy-tip felt marker.

4. Map all 5th-level **TRUE** and **COMPOSITE** watersheds within each 4th-level watershed that contains National Forest System (NFS) land.

   a. First map the true watersheds, which enclose single, integrated stream networks that drain to a watershed outlet (fig. 8).

   b. Next map the composite watersheds, which are groups of tributaries flowing directly into the main stream. Combine them to include similar landforms and fit the size range of the true watersheds. These composite watersheds often span both sides of the main stream. Draw their boundary lines to connect with the mouths of the true watersheds (fig. 8).

5. Coordinate these 5th-level boundaries with the USDA Natural Resources Conservation Service (NRCS) (changed in 1995 from USDA Soil Conservation Service (SCS)). They have mapped 5th-level watersheds for all States, but are usually willing to adjust their boundaries within and adjacent to NFS lands.

6. Repeat step #4 to map all 6th-level watersheds within each 5th-level watershed that contains NFS land. Repeat again for smaller watersheds. Map 5th- and 6th-level watersheds on 1:100,000- and 1:24,000-scale topographic maps. Map smaller watersheds on 1:24,000-scale topographic maps only.

7. Assign two-digit numeric codes to all watersheds of each level, beginning in the headwaters of the larger watershed within which they are nested and working downstream in order of position relative to the main stream (fig. 9). Record watershed codes on paper copies of the topographic maps. Color coding the different levels of watershed boundaries may help avoid confusion.

8. Coordinate watershed boundaries and codes common to other Forests and Regions before finishing your maps. Compare boundaries and codes among the adjoining maps. Boundaries must match exactly at the map neatline.

9. Have the forest hydrologist review the location and rationale of all watershed boundaries, check these lines with fisheries biologists and Ranger District personnel, and revise them if needed before approving the maps. To help reviewers, make notes on the paper quads about the rationale for certain boundaries. Make notes where local knowledge overrides the map data. Check codes for duplication, missing codes, matching, etc.

10. When lines are final, transfer them to pin-registered mylar quads using proper inking and cartographic methods. Use a pen with a line width of about 0.6 mm to draw watershed boundaries. Keep lines dark and consistent with no skips or breaks. On final plain matte mylar overlays, use rub-on crosses to define map corners and place labels in the lower right corner.

These guides show how to map watershed boundaries by hand. You may wish to map electronically using computer programs that

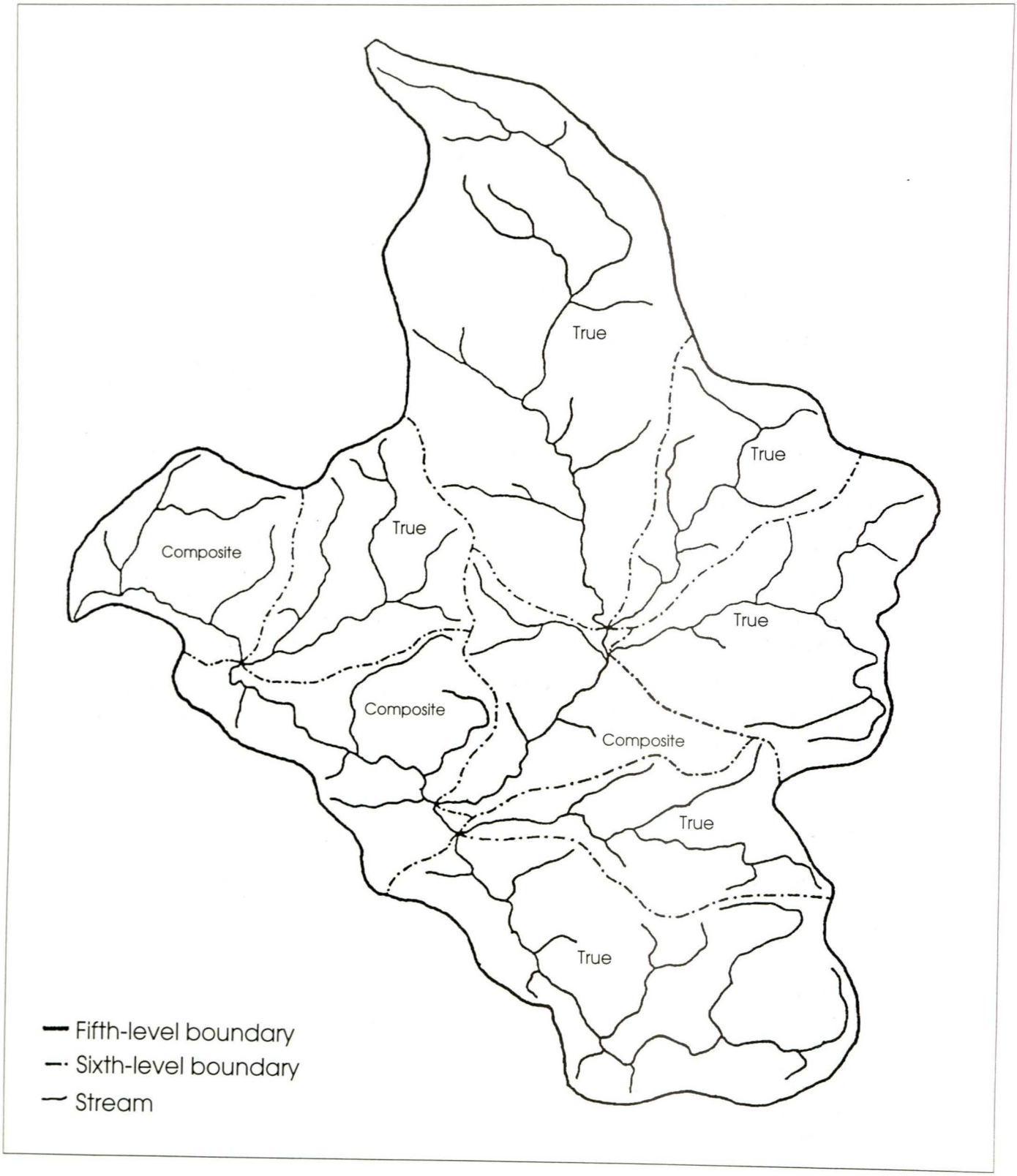


Figure 8.—*Example of watershed delineation.*

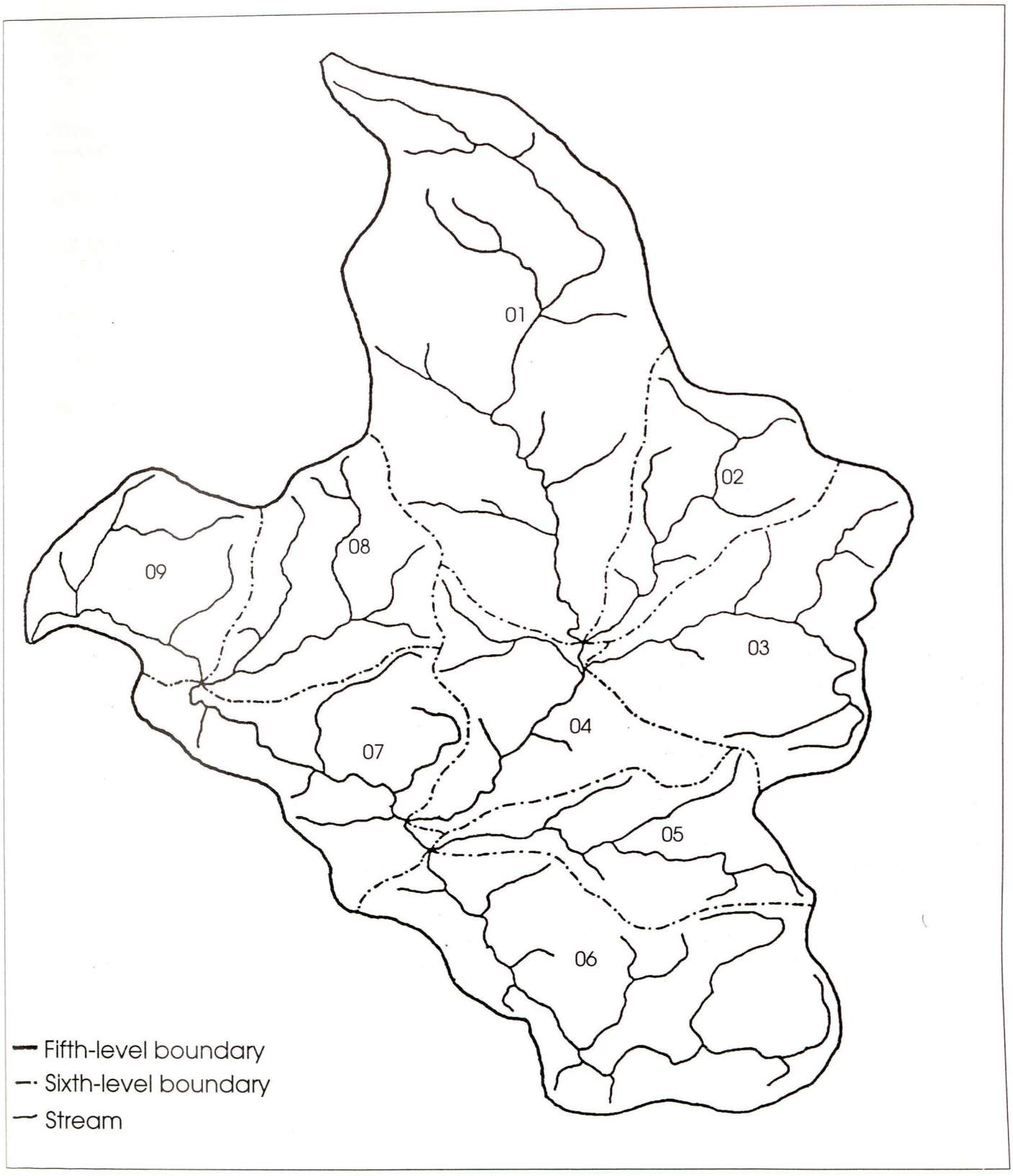


Figure 9.—*Example of watershed coding.*

rely on digital elevation models, or DEM's (Martz and Garbrecht 1993). However, such an approach requires robust computer skills, and lines may not match contours in all types of terrain.

Delineation of Stream Networks

On USGS maps, the drainage network is shown as blue lines (perennial streams are solid, intermittent streams are dashed). Headwater streams in steep terrain that are masked by vegetation are not shown on USGS maps, so most intermittent streams are not depicted. To obtain a truer picture of the actual network of perennial and intermittent streams, the network is extended using contour crenulation.

Scientific Background of Stream Network Delineation

A complete aquatic ecological inventory requires an accurate delineation of the total stream network of all defined channels, wet or dry. Many maps show blue lines for only stream segments with water on the day the aerial photo was taken. Omission of tributary channels and poor placement of channel junctions have long plagued cartographers trying to accurately map stream features (Maxwell 1960).

USGS Blue Line Method.—Stream networks are mapped on USGS 1:24,000-scale topographic quadrangles. The USGS topographic instructions advise mappers generally to pencil in all verified perennial streams, regardless of length, for later office editing (Beaman 1928). Intermittent streams less than 2,000 feet long are usually omitted unless they emanate from springs or water bodies. Streams on 1:24,000-scale maps are usually shown as starting not closer than about 1,000 feet from the divide (USGS 1963).

Stream network complexity or map appearance and scale may determine whether the cartographer included certain intermittent streams (Chorley and Dale 1972). Some ambiguities have arisen in USGS delineation of streams using these methods. It is standard practice to trace all streams in the field or on the photo and then fit contours to the stream pattern. The map is subjectively revised using the significance of contour bends to indicate the existence of stream channels.

Contour Crenulation Method.—Geomorphologists have studied contour-crenulated stream networks and drawn varied conclusions for diverse terrain and map scales. Using 1:24,000-scale topographic maps of the Appalachian Plateaus, Morisawa (1957, 1959) found great discrepancies between field-mapped channels and USGS blue lines, but not between crenulated and field-mapped channels. Scheidegger (1966) found USGS blue lines to be arbitrary and dependent on the observed flow. But Coates (1958), using 1:600-scale topographic maps of southern Illinois with 10-foot contour intervals, found that fingertip tributaries could seldom be map-inferred, most first order streams were really third order, and actual total channel lengths were 3 to 5 times greater than crenulated lengths.

The significance of contour crenulations depends on map accuracy (Chorley and Dale 1972). No accuracy standards for contour crenulations existed before 1980. Differences in geology (lithology and structure) affect stream patterns and densities. Topographic maps and aerial photos of similar type and scale must be used to ensure consistency between investigators.

Mapping Process for Contour Crenulation of Stream Channels

Chorley and Dale (1972) define a contour crenulation as a "fine notch or scallop" in a contour line used to extend channels. Marston (1978) advises streams to be drawn through contours that exhibit a "definite bend." Contour crenulation is actually one step in the four-step process of mapping the true network of defined stream channels that exist on the ground (Bauer 1980, Gardiner 1975). The four steps of this process are:

1. Mapping of blue lines from USGS 1:24,000 maps.
2. Contour crenulation of topographic maps.
3. Interpretation of aerial photos.
4. Field identification.

You will need the following materials for contour crenulation:

1. Primary Base Series (PBS) maps.
2. Blank matte mylars pin-registered to the PBS maps.

3. Rub-on crosses and labels.
4. Pen with line width of about 0.25 mm.
5. Aerial photos or color infrared positive film.

Follow the steps below to complete the total stream network (Way 1978) beyond the existing USGS blue lines, using contour crenulations.

1. Mark a matte mylar template (1 inch by 2 inches) with a 120° angle in light blue pencil. Mark the PBS map corners on the blank pin-registered matte mylars using rub-on crosses. Label the mylars using rub-on labels in the lower right corner. You will crenulate streams on these matte mylars.

2. Begin crenulating at the end of each existing blue line (solid or dashed) stream channel on the map. Read every contour unless the contour interval is less than 20 feet (read every other contour if the interval is 10 feet). Use a pen with a line width of about 0.25 mm. A contour bend must form an angle of 120° or less to be counted.

3. When two or more consecutive contours form an angle of 120° or less pointing upstream or upslope from an existing stream channel, extend a line that bisects the contour bends to depict the added stream channel(s).

4. If a valley upstream or upslope from an existing stream channel meets conditions of #3 but is separated from the existing network by one or two contours with an angle more than 120°, connect the crenulated channel to the existing network by extending its line to bisect the contour bends. If the valley is separated from the existing network by three or more contours, proceed to #5.

5. If landforms or vegetation on aerial photos (color infrared positive film with a light table is recommended) show that the crenulated channel length is connected to the existing network, connect the channel by drawing its line to bisect the contour bends. If such photo indicators are absent, go to #6.

6. If the disconnected channel is second order or larger (see below), or is first order and 10 mm or longer on the map (800 feet or longer on the ground), keep the channel on the map and denote it as a disconnected channel by labeling it with a "DC" in non-scannable blue pencil. If these conditions are not met, erase the channel from the map.

7. Perform contour crenulation in each 6th-level watershed that has NFS land. Exactly match crenulated streams on adjoining maps at the map neatline.

These steps work well in most cases except for small fingertip tributaries in badlands or densely forested terrain. Even with the most rigorous standards, map scale affects how well crenulated and true networks match. Topographic maps at 1:24,000 seem to represent stream networks well in medium-textured terrain, but not in dense-textured badland terrain where, even in the field, rills and fingertip channels are hard to distinguish (Chorley and Dale 1972).

These steps are used to map streams by hand. However, you may wish to map electronically using computer programs that rely on digital elevation models, or DEM's (Martz and Garbrecht 1993). But this approach requires robust computer skills, and lines may not match contours in all types of terrain.

Stream Orders and Link Numbers

Stream orders (Strahler 1957) are used to apply laws of drainage composition to morphometric analysis of watersheds and hydrologic processes (Gregory and Walling 1973). Link numbers (Shreve 1966) are used to describe the total stream network in relation to flow amounts (Gregory and Walling 1973). These systems help users understand streamflow, stream power, and sediment yield characteristics of a watershed and its streams (figs. 10 and 11).

Watershed Morphology

Attributes of watershed morphology are physical geomorphic descriptors of the watershed and stream network controlled by climatic and geologic factors. These attributes help us interpret functional links between watersheds, streamflows, sediment yields, and aquatic habitats (Baker 1989, Marston 1978, Rogers and Singh 1986).

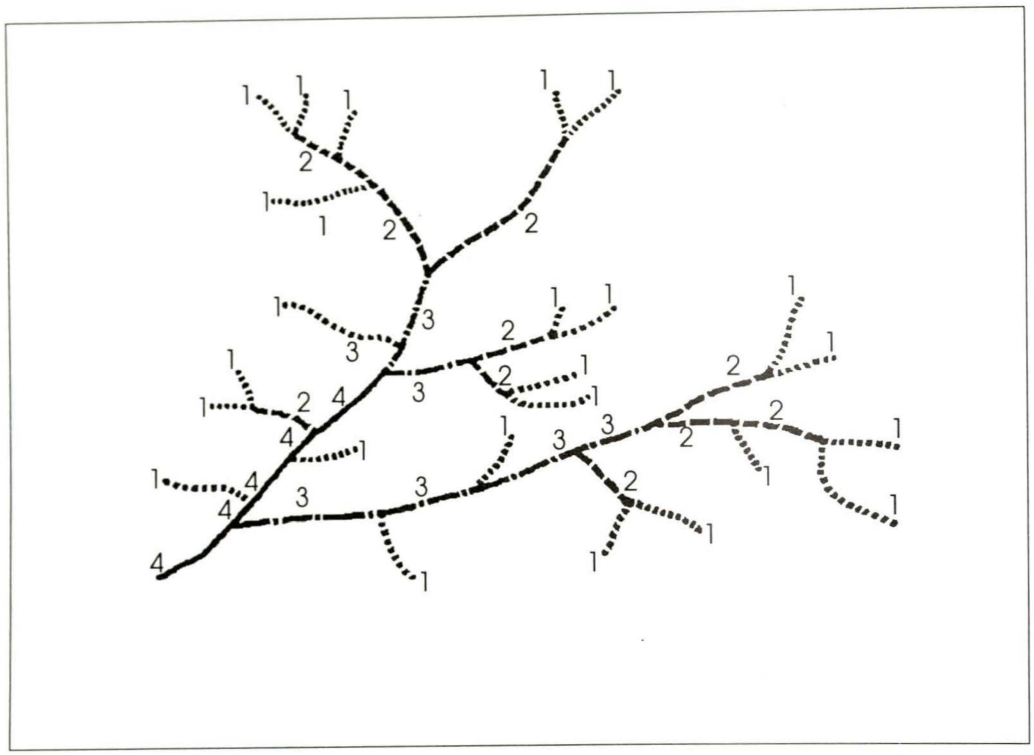


Figure 10.—*Stream orders (after Strahler 1957).*

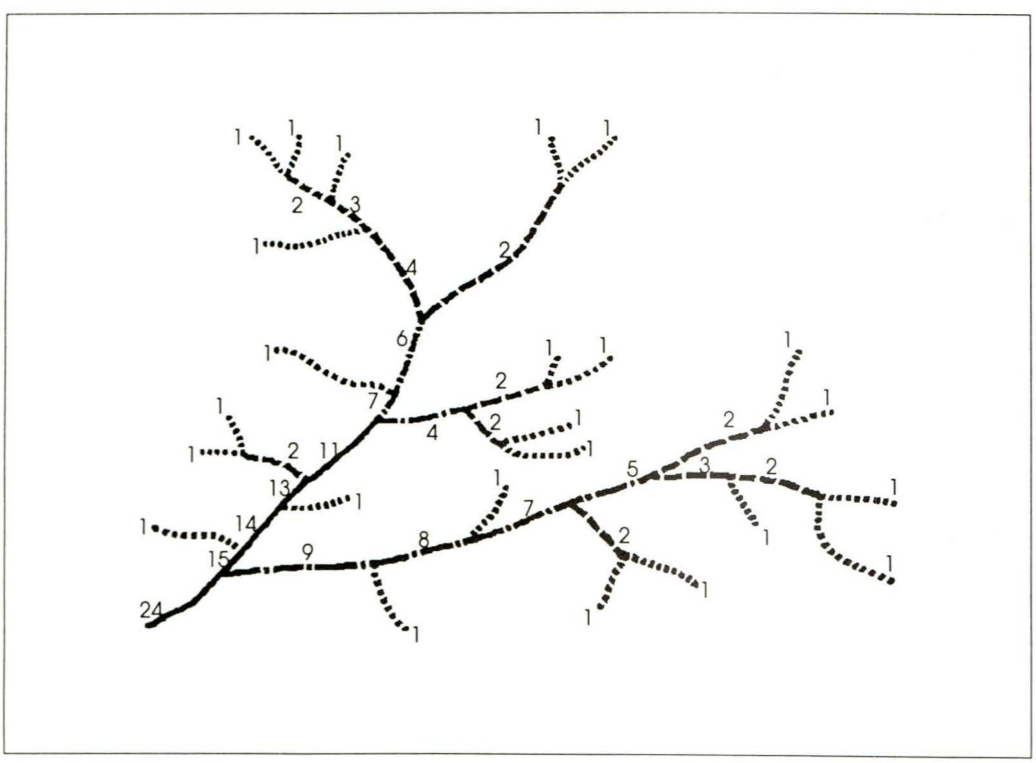


Figure 11.—*Stream link numbers (after Shreve 1966).*

Geomorphic variables used to quantify watershed morphology differ among authors. Geomorphologists have long recognized the importance of developing quantitative mathematical descriptions of watershed morphology. Horton (1945) first assigned stream orders to the stream network. Strahler (1964) and Chorley (1969) recognized watersheds as basic morphometric units and identified areal, relief, and gradient attributes. Marston (1978) identified morphometric variables that had been used in the literature.

Watershed morphometric variables are needed for two reasons. First, they are used to classify watersheds into groups of similar geomorphic character. This is important in distinguishing groups of watersheds that differ from each other in their hydrologic response. Second, these variables can be used to predict flow parameters, sediment yields, and aquatic habitat relationships in watersheds (Heller *et al.* 1983, Maxwell and Marston 1980).

The following attributes allow important hydrologic and aquatic interpretations to be made. They are grouped into basin variables, stream network variables, and variables relating the stream network to the basin. Some of the stream network variables cannot be reliably computed for first- or second-order watersheds.

Basin Morphometric Variables

Basin area.—Watershed area in square kilometers (Horton 1945, Schumm 1956).

Basin perimeter.—Watershed circumference in kilometers (Smith 1950, USGS 1977).

Maximum elevation.—Highest point on watershed divide in meters (Schumm 1956).

Minimum elevation.—Elevation at stream mouth in meters (Schumm 1956).

Mean elevation.—Area-weighted mean watershed elevation, derived by summing the products of planimetered subareas between major contour intervals and their median elevations, and dividing this sum by basin area (USGS 1977).

Mean slope.—Area-weighted mean watershed slope, derived by multiplying total contour length by contour interval, and dividing by basin area (Wisler and Brater 1959).

Basin length.—Airline distance from outlet through the head of the longest watercourse to the basin perimeter, in kilometers (Potter 1961, USGS 1977).

Basin relief.—Difference between maximum and minimum elevation along basin length in meters (Chorley 1969, Schumm 1956).

Basin aspect.—Azimuth of line describing basin length in degrees (Horton 1932, USGS 1977).

Compactness coefficient.—Watershed perimeter divided by circumference of circle with same area (Rothacher *et al.* 1967).

Lemniscate.—Square of basin length divided by four times basin area (Chorley *et al.* 1957).

Glacier area.—Percent of watershed area in glaciers.

Lake area.—Percent of watershed area in lakes.

Stream Network Morphometric Variables

Number of nth order streams.—Total number of streams of each order (Strahler 1957).

Length of nth order streams.—Total length of streams of each order in kilometers.

Total stream length.—Sum of total stream lengths of all orders in kilometers (Horton 1945).

Total stream relief.—Sum of total stream reliefs of all orders in kilometers (Horton 1945).

Bifurcation ratio.—Average ratio of number of streams of each order to number of streams of next higher order (Horton 1945).

Stream length ratio.—Average ratio of mean length of streams of each order to mean length of streams of next higher order (Horton 1945).

Stream relief ratio.—Average ratio of mean relief of streams of each order to mean relief of streams of next higher order (Schumm 1956).

Morphometric Variables Relating Stream Network to Basin

Drainage density.—Total stream length divided by basin area in kilometers per square kilometer (Horton 1945).

Stream frequency.—Total number of streams of all orders divided by basin area in number per square kilometer (Horton 1945).

Drainage relief.—Total stream relief divided by watershed perimeter.

Longitudinal profile.—Plot of stream length versus elevation from the mouth of the main stem up to the head of any first-order stream in the watershed.

APPENDIX B

LARGE LAKES IN NORTH AMERICA

Tables 5 and 6 contain information about distribution and selected morphometric attributes of large lakes in North America (compiled from Herdendorf 1984). The **location** column refers to the map in figure 12.

Table 5.—*Lakes in North America that are larger than 10,000 km² in area*

Lake	Area (km²)	Elev (m)	Depth (m)		Location	Genesis
			Mean	Max		
Superior	82,100	183	149	407	C/U 1	G
Huron	59,500	177	59	229	C/U 2	G
Michigan	57,750	177	85	282	USA 3	G
Great Bear	31,326	156	76	452	Can 4	G
Great Slave	28,568	156	73	625	Can 5	G
Erie	25,657	174	19	64	C/U 6	G
Winnipeg	24,387	217	14	18	Can 7	G
Ontario	19,000	75	86	245	C/U 8	G

Table 6.—*Lakes in North America that are between 1,000 and 10,000 km² in area*

Lake	Area (km²)	Elev (m)	Depth (m)		Location	Genesis
			Mean	Max		
Nicaragua	8,150	32	13	70	Nic 9	T
Athabasca	7,935	213	26	120	Can 10	G
Reindeer	6,640	337	17	219	Can 11	G
Netilling	5,530	30	—	—	Can 12	G
Winnipegosis	5,375	254	3	12	Can 13	G
Nipigon	4,848	320	—	165	Can 14	G
Manitoba	4,625	248	3	4	Can 15	G
Great Salt	4,360	1,260	4	15	USA 16	T
Woods	4,350	323	8	21	Can 17	G
Dubawnt	3,833	236	—	—	Can 18	G
Amadjuak	3,115	113	—	—	Can 19	G
Melville	3,069	0	—	256	Can 20	C
Wollaston	2,690	398	17	97	Can 21	G
Iliamna	2,590	15	—	299	USA 22	G
Mistassini	2,335	372	—	183	Can 23	G
Nueltin	2,279	278	—	—	Can 24	G
South Indian	2,247	254	—	18	Can 25	G
Michikamua	2,030	460	—	80	Can 26	G
Baker	1,887	2	—	230	Can 27	G
Okeechobee	1,810	6	—	6	USA 28	T
Martre	1,776	265	—	—	Can 29	G
Seul	1,658	357	8	34	Can 30	G
Pontchartrain	1,620	1	—	5	USA 31	F
Terminos	1,550	0	—	1	Mex 32	C
Yathkyed	1,449	140	—	—	Can 33	G

(Table 6 continued on next page)

(Table 6 continued)

Lake	Area (km²)	Elev (m)	Depth (m)		Location	Genesis
			Mean	Max		
Cree	1,440	487	15	60	Can 34	G
Claire	1,436	213	1	2	Can 35	G
Ronge	1,413	364	13	38	Can 36	G
Selawik	1,400	0	—	—	USA 37	C
Eau Claire	1,383	283	—	—	Can 38	G
Moose	1,367	255	—	—	Can 39	G
Cedar	1,353	253	—	—	Can 40	G
Kasba	1,341	336	—	—	Can 41	G
Bienville	1,249	391	—	—	Can 42	G
Island	1,223	227	—	—	Can 43	G
St. Clair	1,210	175	4	7	C/U 44	G
Becharof	1,190	4	—	92	USA 45	G
Red	1,170	358	6	9	USA 46	G
Lesser Slave	1,169	577	12	21	Can 47	G
Gods	1,151	178	—	—	Can 48	G
Chapala	1,140	1,525	9	13	Mex 49	T
Caratasca	1,110	0	—	5	Hon 50	C
Aberdeen	1,100	80	—	—	Can 51	G
Bras D'Or	1,100	0	—	70	Can 52	C
Champlain	1,100	30	—	122	C/U 53	T
Takiyuak	1,080	381	—	—	Can 54	G
Mackay	1,061	431	—	—	Can 55	G
Managua	1,040	37	—	80	Nic 56	T
St. Jean	1,003	98	—	63	Can 57	G

Location codes: *USA = United States (including Alaska)*
Can = Canada
C/U = Canada-USA
Nic = Nicaragua
Mex = Mexico
Hon = Honduras

Genesis codes: *G = glacial scour*
T = tectonic
C = coastal lagoon
F = fluviatile

Conversions: *acres = 247.1 x km²*
feet = 3.281 x meters

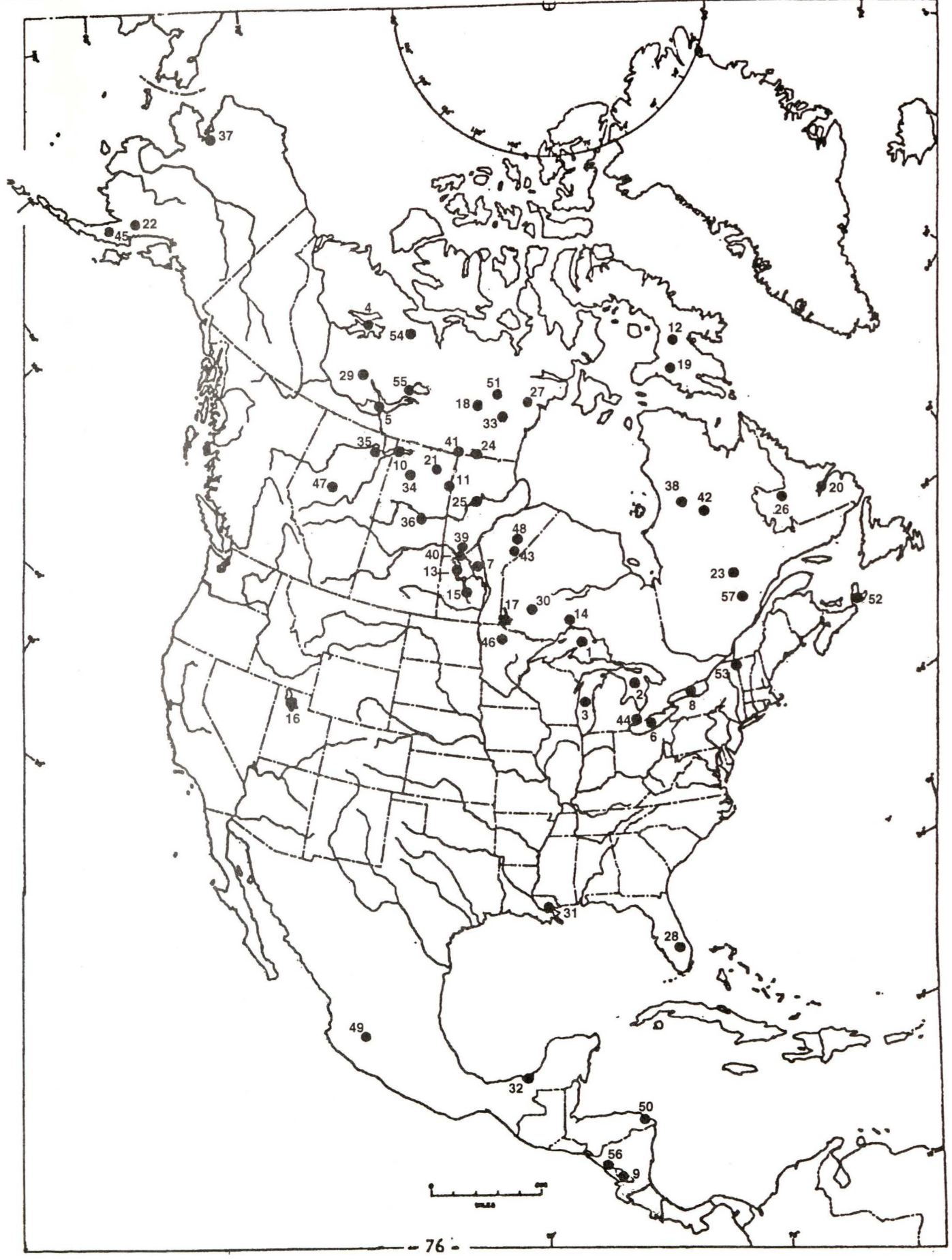


Figure 12.—*Large lakes in North America (from Herdendorf 1984). Numbers are cross referenced to tables 5 and 6.*

APPENDIX C

GROUND-WATER HYDROGEOLOGIC SETTINGS

This appendix lists the 111 hydrogeologic settings (Aller *et al.* 1987) known to exist within the 13 ground-water regions in the United States (Heath 1984). The hydrogeologic settings are mapping units that should be used to help delineate terrestrial subsections and landtype associations (USDA 1993). Full descriptions of these hydrogeologic settings are found in Aller *et al.* (1987).

Western Mountain Ranges
- Mountain slopes (east and west)
- Alluvial mountain valleys (east and west)
- Mountain flanks (east and west)
- Glacial mountain valleys
- Wide alluvial valleys (east and west)
- Coastal beaches
- Swamp/marsh
- Mud flows

Alluvial Basins
- Mountain slopes
- Alluvial mountain valleys
- Alluvial fans
- Alluvial basins (internal drainage)
- Playa lakes
- Swamp/marsh
- Coastal lowlands
- River alluvium (with and without overbank deposits)
- Mud flows
- Alternative sandstone-and-shale sequences
- Continental deposits

Columbia Lava Plateau
- Mountain slopes
- Alluvial mountain valleys
- Hydraulically connected lava flows
- Lava flows not connected hydraulically
- Alluvial fans
- Swamp/marsh
- River alluvium

Colorado Plateau and Wyoming Basin
- Resistant ridges
- Consolidated sedimentary rock
- River alluvium
- Alluvium and dune sand
- Swamp/marsh

High Plains
- Ogallala
- Alluvium
- Sand dunes
- Playa lakes
- Braided river deposits
- Swamp/marsh
- River alluvium (with and without overbank deposits)
- Alternating sandstone-limestone-shale sequences

Non-Glaciated Central
- Mountain slopes
- Alluvial mountain valleys
- Mountain flanks
- Alternating sandstone-limestone-shale (thin soil and deep regolith)
- Solution limestone
- River alluvium (with and without overbank deposits)
- Braided river deposits
- Triassic basins
- Swamp/marsh
- Metamorphic-igneous domes and fault blocks
- Unconsolidated and semi-consolidated aquifers

Glaciated Central
- Glacial till (over bedded sedimentary rock, outwash, solution limestone, sandstone, and shale)
- Outwash (over sequences of fractured sedimentary rock, bedded sedimentary rock, and solution limestone)
- Moraine
- Buried valley
- River alluvium (with and without overbank deposits)
- Glacial lake deposits
- Thin till over bedded sedimentary rock
- Beaches, beach ridges, and sand dunes
- Swamp/marsh

Piedmont and Blue Ridge
- Mountain slopes
- Alluvial mountain valleys
- Mountain flanks
- Regolith
- River alluvium
- Mountain crests
- Swamp/marsh

Northeast and Superior Uplands

- Mountain slopes
- Alluvial mountain valleys
- Mountain flanks
- Glacial till (over crystalline bedrock and outwash)
- Outwash
- Moraine
- River alluvium (with and without overbank deposits)
- Swamp/marsh
- Bedrock uplands
- Glacial lake-marine deposits
- Beaches, beach ridges, and sand dunes

Atlantic and Gulf Coastal Plain

- Regional aquifers
- Unconsolidated and semi-consolidated shallow surficial aquifers
- River alluvium (with and without overbank deposits)
- Swamp

Southeast Coastal Plain

- Solution limestone and shallow surficial aquifers
- Coastal deposits
- Swamp
- Beaches and bars

Hawaii

- Mountain slopes
- Alluvial mountain valleys
- Volcanic uplands
- Coastal beaches

Alaska

- Alluvium
- Glacial and glaciolacustrine deposits of the interior valleys
- Coastal lowland deposits
- Bedrock of the uplands and mountains

APPENDIX D

GLOSSARY

Allochthonous.—Derived from outside a system, such as leaves of terrestrial plants that fall into a stream (Meehan 1991).

Alluvium.—A general term for all detrital deposits resulting directly or indirectly from the sediment transport of (modern) streams, thus including the sediments laid down in riverbeds, flood plains, lakes, fans, and estuaries (USGS 1978).

Aquatic ecosystem.—Waters of the United States, including wetlands, that serve as habitat for interrelated and interacting communities and populations of plants and animals (40 CFR 230.3). The stream channel, lake or estuary bed, water, biotic communities and the habitat features that occur therein (USFS 2526.05).

Aquifer.—A formation, group of formations, or part of a formation that contains sufficient saturated permeable material to yield significant quantities of water to wells and springs (Lohman *et al.* 1972).

Autochthonous.—Derived from within a system, such as organic matter in a stream resulting from photosynthesis by aquatic plants (Meehan 1991).

Backwater pool.—(a) A pool formed by an eddy along channel margins downstream from obstructions such as bars, rootwads, or boulders, or resulting from back flooding upstream from an obstruction; sometimes separated from the channel by sand/gravel bars.

(b) A body of water, the stage of which is controlled by some feature of the channel downstream from the backwater, or in coves or covering low-lying areas and having access to the main body of water (AFS 1985).

Bedload.—Material moving on or near the stream bed by rolling, sliding, and sometimes making brief excursions into the flow a few diameters above the bed (USGS 1978).

Bed roughness.—Measure of the irregularity of stream bed materials as they contribute to resistance to flow; commonly measured in terms of Manning's roughness coefficient

Benthos.—Animals and plants living on or within the substrate of a water body (freshwater, estuarine, or marine) (Meehan 1991).

Bog.—Waterlogged, spongy ground, consisting primarily of mosses, containing acidic decaying vegetation such as sphagnum, sedges, and heaths, which develops into peat (SCS 1993).

Cascade.—Habitat type characterized by swift current, exposed rocks and boulders, high gradient, and considerable turbulence and surface agitation, and consisting of a stepped series of drops (see Rapids and Riffle) (AFS 1985).

Chute.—(a) A narrow confined channel through which water flows rapidly; a rapid or quick descent in a stream, usually with bedrock substrate.

(b) A short straight channel that bypasses a long bend in a stream and that is formed by the stream breaking through a narrow land area between two adjacent bends (AFS 1985).

Classification criteria (differentia).—A map unit delineation, either polygon or line segment, that represents an area dominated by one or more taxa.

Delta.—A deposit of sediment formed where moving water is slowed by a body of standing water (USGS 1978).

Deposition.—The mechanical processes through which sediments accumulate in a resting place (USGS 1978).

Drainage basin.—The area tributary to or draining to a lake, stream, or measuring site (see Watershed) (USGS 1978).

Drainage density.—Length of all channels above those of a specified stream order per unit of drainage area (Langbein 1960).

Ecological site.—A specific location on the land or water that is representative of an ecological type (USFS 1991).

Ecological type.—A category of land or water having a unique combination of biotic and abiotic features differing from other ecological types in its ability to produce vegetation and respond to management. Categories of ecological types include all sites that have this unique combination of components with the defined ranges of properties (USFS 1991).

Ecological unit.—A mapped landscape or aquatic unit comprised of one or more ecological types (USFS 1991).

Ecosystem.—A complete interacting system of organisms and their environment (USFS 1991).

Eddy.—A circular current of water, sometimes quite strong, diverging from and initially flowing contrary to the main current. It is usually formed at a point at which the flow passes some obstruction or on the inside of river bends. Often forms backwater pools or pocket water in riffles (AFS 1985).

Erosion.—The wearing away of the land surface by detachment and movement of soil and rock fragments through the action of moving water and other geological agents (USGS 1978).

Estuarine system.—Deepwater tidal habitats and adjacent tidal wetlands, which are usually semienclosed by land but have open, partly obstructed, or sporadic access to the open ocean, and in which ocean water is at least occasionally diluted from freshwater runoff from the land (Cowardin *et al.* 1992).

Eutrophic.—Rich in dissolved nutrients, photosynthetically productive, and often deficient in oxygen during warm periods (Meehan 1991).

Flood plain.—The lowland that borders a river, usually dry but subject to flooding. That land outside of a stream channel described by the perimeter of the maximum probable flood (Langbein 1960).

Fluvial.—(1) Pertaining to streams. (2) Growing or living in streams or ponds. (3) Produced by river action, as a fluvial plain (USGS 1978).

Glide.—A slow moving, relatively shallow type of run. Calm water flowing smoothly and gently, with moderately low velocities (10 to 20 cm/sec), and little or no surface turbulance (see Rapids, Riffle and Run) (AFS 1985).

Ground water.—Water in the ground that is in the zone of saturation, from which wells and springs and ground-water runoff are supplied (Langbein 1960).

Ground water, confined.—Ground water under pressure significantly greater than atmospheric. Its upper limit is the bottom of a bed of distinctly lower hydraulic conductivity than that of the material in which the confined water occurs (Lohman *et al.* 1972).

Ground water, perched.—Unconfined ground water separated from an underlying body of ground water by an unsaturated zone; having a perched water table that is held up by a perching bed whose permeability is so low that water percolating downward through it is not able to bring water in the underlying unsaturated zone above atmospheric pressure. Perched ground water may be permanent, where recharge is frequent enough to maintain a saturated zone above the perching bed; or it may be temporary, disappearing from time to time as a result of drainage over the edge of or through the perching bed (Lohman *et al.* 1972).

Ground water, unconfined.—Unconfined ground water is water in a aquifer that has a water table (Lohman *et al.* 1972).

Hierarchical classification.—A classification technique in which each, more detailed level, falls within the delineation of the next higher level class. Predictable and repeatable properties of a given level in the classification are defined by the next higher level (USFS 1991).

Hypolimnion.—Lowermost, noncirculating layer of cold water in a thermally stratified lake, usually deficient in oxygen (Meehan 1991).

Hyporheic zone.—The layer of stream channel substrate extending as deep as there is interstitial flow (AFS 1985).

Lacustrine system.—Wetlands and deep water habitats with all the following characteristics: (1) situated in a topographic depression or a dammed river channel; (2) lacking trees, shrubs, persistent emergents, emergent mosses or lichens with greater than 30 percent aerial coverage; and (3) total area exceeds 8 ha (Cowardin *et al.* 1992).

Large woody debris.—Any large piece of relatively stable woody material with a diameter greater than 10 cm and longer than 1m that intrudes into or is contained within the steam channel. Synonyms: LOD, large organic debris, LWD, log (AFS 1985).

Littoral zone.—Region along the shore (Meehan 1991).

Macroinvertebrates.—Invertebrates large enough to be seen with the naked eye (e.g., most aquatic insects, snails, and amphipods) (Meehan 1991).

Macrophytes.—Plants large enough to be seen with the naked eye (Meehan 1991).

Mapping units (stream).—A map unit delineation, either polygon or line segment, that represents an area dominated by one or more taxa. Stream mapping unit design must take into account the information needs and management objectives for a given level of stream inventory. Mapping units contain inclusions of taxa that have both similar and dissimilar (contrasting) properties. These inclusions of taxa may be small areas that are not practical to show as separate units or associated taxa that are combined as one unit because management interpretations are similar.

Map unit description (MUD).—Description of the range of properties for each map delineation. MUDS should identify the special distribution and percent composition of dominant taxa, as well as mapping inclusions. Fluvial process, functions, and temporal relationships should be discussed. Mapping scale and categorical level of the mapping unit will largely define the variability of properties described in the MUD.

Microhabitat.—That specific combination of habitat elements in the location selected by organisms for specific purposes and/or events. Expresses the more specific and functional aspects of habitat and cover. Separated from adjoining microhabitats by distinctive physical characteristics such as velocity, depth, and cover (AFS 1985).

Oligotrophic.—Poor in dissolved nutrients, of low photosynthetic productivity, and rich in dissolved oxygen at all depths (see Eutrophic) (Meehan 1991).

Palustrine system.—All nontidal wetlands dominated by trees, shrubs, persistent emergents, emergent mosses or lichens, and all wetlands that occur in tidal areas where salinity due to ocean derived salt is below 0.5 percent. Also includes wetlands lacking such vegetation, but with all the following four characteristics: (1) area less than 8 ha; (2) active water-formed or bedrock shoreline features lacking; (3) water in deepest part of basin less than 2 m deep at low water; (4) salinity due to ocean derived salt less than 0.5 percent (Cowardin *et al.* 1992).

Pelagic.—Of or in open waters of lakes or seas (Meehan 1991).

pH.—A measure of the hydrogen-ion activity in a solution, expressed as the negative $\log_{10}$ of hydrogen ion concentration on a scale of 0 (highly acidic) to 14 (highly basic); a pH of 7 is neutral (Meehan 1991).

Plunge pool.—A pool created by water passing over or through a complete or nearly complete channel obstruction, and dropping vertically, scouring out a basin in which flow radiates from the point of water entry (AFS 1985).

Pool.—(a) A portion of the stream with reduced current velocity, often with water deeper than the surrounding areas; frequently usable by fish for resting and cover.

(b) A small body of standing water, e.g., in a marsh or on the flood plain (see Glide, Rapids, Riffle) (AFS 1985).

Potential natural community.—The biotic community that would be established if all successional sequences of its ecosystem

were completed without additional human-caused disturbance under present environmental conditions. Grazing by native fauna, as well as natural disturbances such as drought, flood, wildfire, insects, and disease are inherent in the development of potential natural communities, which may include naturalized non-active species (USFS 1991).

Rapids.—A relatively deep stream section with considerable surface agitation and swift current. Some waves may be present. Rocks and boulders may be exposed at all but high flows. Drops up to 1 m (see Glide, Riffle, Run) (AFS 1985).

Riffle.—A shallow rapids where the water flows swiftly over completely or partly submerged obstructions to produce surface agitation, but standing waves are absent (see Glide, Rapids, Run) (AFS 1985).

Riparian.—Pertaining to anything connected with or immediately adjacent to the banks of a stream or other body of water (AFS 1985).

Riparian vegetation.—Vegetation growing on or near the banks of a stream or other body of water in soils that exhibit some wetness characteristics during some portion of the growing season (Meehan 1991).

River continuum.—Gradual changes in the biological community of a river as energy sources and physical conditions change from headwaters to lowlands (Meehan 1991).

Riverine system.—All wetlands and deepwater habitats contained within a channel, with two exceptions: (1) wetlands dominated by trees, shrubs, persistent emergents, emergent mosses, or lichens; and (2) habitats with water containing ocean derived salts in excess of 0.5 percent (Cowardin *et al.* 1992).

Run.—An area of swiftly flowing water, without surface agitation or waves, which approximates uniform flow and in which the slope of water surface is roughly parallel to the overall gradient of the stream reach (see Glide, Rapids, Riffle) (AFS 1985).

Runoff.—Flow that is discharged from the area by stream channels—sometimes subdivided into surface runoff and seepage (USGS 1978).

Scour.—The enlargement of a flow section by removal of boundary material through the action of fluid in motion (USGS 1978).

Sediment load.—A general term that refers to material in suspension and/or in transport. It is not synonymous with either discharge or concentration (USGS 1978). See table 7 on page 60 for particle size distributions.

Stock.—Group of fish that is genetically self-sustaining and isolated geographically or temporally during reproduction (Meehan 1991).

Stream.—A general term for a body of flowing water. In hydrology the term is generally applied to the water flowing in a natural channel as distinct from a canal. More generally as in the term stream gauging, it is applied to the water flowing in any channel, natural or artificial (Langbein 1960).

Streams in natural channels may be classified as follows:

Relation to time.

- **Perennial**: One that flows continuously.
- **Intermittent or seasonal**: One that flows only at certain times of the year when it receives water from springs or from some surface source such as melting snow in mountainous areas.
- **Ephemeral**: One that flows only in direct response to precipitation, and whose channel is at all times above the water table.

Relation to space.

- **Continuous**: One that does not have interruptions in space.
- **Interrupted**: One that contains alternating reaches that are either perennial, intermittent, or ephemeral.

Relation to ground.

- **Gaining**: A stream or reach of a stream that receives water from the zone of saturation.
- **Losing**: A stream or reach of a stream that contributes water to the zone of saturation.

- **Insulated**: A stream or reach of a stream that neither contributes water to the zone of saturation nor receives water from it; separated from the zones of saturation by an impermeable bed.
- **Perched**: A losing stream or an insulated stream that is separated from the underlying ground water by a zone of aeration.

Stream order.—A method of numbering steams as part of a drainage basin network. The smallest unbranched mapped tributary is called first order, the stream receiving the tributary is called second order, and so on. It is usually necessary to specify the scale of the map used. A 1st-order stream on a 1:62,500 map may be a 3rd-order stream on a 1:212,000 map (Langbein 1960).

Suspended sediment.—Sediment that is carried in suspension by the turbulent components of the fluid or by Brownian movement (USGS 1978).

Thermocline.—Layer of water between the warmer surface zone and the colder deep zone of a thermally stratified body of water. In the thermocline, temperature decreases rapidly with depth (Meehan 1991).

Trophic level.—Stage in a food chain or web leading from primary producers (lowest trophic level) through herbivores to primary and secondary carnivores (consumers-highest level) (Meehan 1991).

Watershed.—All lands enclosed by a continuous hydrologic-surface drainage divide and lying upslope from a specified point on a stream (see Drainage basin) (USGS 1978).

Water table.—That surface in a ground-water body at which the water pressure is atmospheric (Lohman *et al.* 1972).

Wetlands.—Those areas inundated or saturated by surface or ground water at a frequency and duration sufficient to support, and under normal circumstances they do support, a prevalence of vegetation typically adapted for life in saturated soil conditions; generally include swamps, marshes, bogs, and similar areas (40 CFR 230.3). Lands transitional between terrestrial and aquatic systems where the water table is usually at or near the surface or the land is covered by shallow water; must have one or more of the following characteristics: (1) at least periodically, the land supports predominantly hydrophytes; (2) the substrate is predominantly undrained hydric soil; (3) the substrate is nonsoil and is saturated with water or covered by shallow water at some time during the growing season of each year (Cowardin *et al.* 1992).

Table 7.—*Scale of particle sizes for sediment (from USGS 1978). (See Sediment Load.)*

Class name	Size (mm)	Phi value
Boulder	>256	<—8
Cobble	256 - 64	-8 to -6
Gravel	64 - 2	-6 to -1
Very coarse sand	2.0 - 1.0	-1 to 0
Coarse sand	1.0 - 0.50	0 to +1
Medium sand	0.50 - 0.25	+1 to +2
Fine sand	0.25 - 0.125	+2 to +3
Very fine sand	0.125 - 0.062	+3 to +4
Silt	0.062 - 0.004	+4 to +8
Clay	0.004 - 0.0002420	+8 to +12
Colloid	< 0.00024	> +12

APPENDIX E

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Maxwell, James R.; Edwards, Clayton J.; Jensen, Mark E.; Paustian, Steven J.; Parrott, Harry; Hill, Donley M.

1995. **A hierarchical framework of aquatic ecological units in North America (Nearctic Zone).** Gen. Tech. Rep. NC-176. St. Paul, MN: U.S. Department of Agriculture, Forest Service, North Central Forest Experiment Station. 72 p.

Proposes a framework for classifying and mapping aquatic systems at various scales using ecologically significant physical and biological criteria. Classification and mapping concepts follow tenets of hierarchical theory, pattern recognition, and driving variables. Criteria are provided for the hierarchical classification and mapping of aquatic ecological units of riverine, lacustrine, and ground-water systems within their geoclimatic and watershed settings. Some hydrogeomorphic criteria for classifying wetlands are also proposed.

KEY WORDS: Aquatic ecology, hierarchical classification, watershed, fish, mussels, streams, rivers, ground water, wetlands, lakes.

Our job at the North Central Forest Experiment Station is discovering and creating new knowledge and technology in the field of natural resources and conveying this information to the people who can use it. As a new generation of forests emerges in our region, managers are confronted with two unique challenges: (1) Dealing with the great diversity in composition, quality, and ownership of the forests, and (2) Reconciling the conflicting demands of the people who use them. Helping the forest manager meet these challenges while protecting the environment is what research at North Central is all about.